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## SOIL SCIENCE

### Contents for June, 1920

WILLIAM H. MARTIN. The Relation of Sulfur to Soil Acidity and to the Control of Potato Scab.....	393
M. I. WOLKOFF. Effect of Various Soluble Salts and Lime on Evaporation. Capillary Rise and Distribution of Water in Some Agricultural Soils.....	409
THAKUR MAHADEO SINGH. The Effect of Gypsum on Bacterial Activities in Soils....	437
BURTON E. LIVINGSTON AND RIICHIRO KOKETSU. The Water-Supplying Power of the Soil as Related to the Wilting of Plants.....	469
CHARLES E. THORNE. Carriers of Nitrogen in Fertilizers .....	487
INDEX.....	495

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## THE RELATION OF SULFUR TO SOIL ACIDITY AND TO THE CONTROL OF POTATO SCAB<sup>1</sup>

WILLIAM H. MARTIN

*New Jersey Agricultural Experiment Station*

Received for publication April 13, 1920

### INTRODUCTION

Potato scab, caused by *Actinomyces chromogenus* Gasperini, is no doubt, the most common disease of this important agricultural crop. The disease was first mentioned in Loudon's Encyclopedia of Agriculture (18) as follows: "Scab, that is to say, the ulceration of the surface of the tubers, has never been explained in a satisfactory manner. Some attribute it to the ammonia from the dung of the horse, others to alkali, and certain others to the use of wood ashes on the soil. Not using diseased seed and planting on other soil are the only known means of preventing the malady." Since this first mention of the disease an extensive literature has appeared on the subject, a large portion of which has been devoted to control measures.

On the tuber, satisfactory control has been secured by treating with either formaldehyde or corrosive sublimate. Where the scab organism, is present in the soil, however, as is very frequently the case where potatoes are grown for a number of years on the same land, seed treatment is of little value. Where this condition exists, control measures must be based on eradicating the organism from the soil. This fact has long been recognized, and Halsted (10, 11, 12, 13, 14), one of the first to conduct investigations on this subject, found from his tests with various soil germicides that sulfur was the only one which gave results that would warrant its use for this purpose.

Further investigations by Halsted and others, have shown contradictory results in the use of sulfur for the control of scab. Halsted (10, 11, 12, 13, 14) reports a marked decrease in the amount of scab following an application of 300 pounds of sulfur per acre, while a similar quantity under different conditions had no beneficial effect. In another experiment, an application of 600 pounds of sulfur in 1896 had no effect on scab in that or the succeeding year; in 1898 however, the sulfur became effective, bringing about a reduction of 36.1 per cent in the amount of scab.

In an experiment conducted in the greenhouse, Garman (6) found no difference in the amount of scab where untreated seed pieces, and seed pieces

<sup>1</sup> Technical Paper No. 3 of the New Jersey Agricultural Experiment Stations Department of Plant Pathology.

rolled in sulfur flour, were planted in sterile soil. Field experiments where sulfur was used at the rate of 150 and 180 pounds per acre likewise showed no indicative results. His results were corroborated by Brooks (3) who reports failure in the use of sulfur for the control of scab.

As a result of a series of experiments, in which sulfur was used at the rate of 300 pounds per acre following an application of 600 pounds in the preceding year, Wheeler and Adams (22) conclude that: "The indications are that the sulfur treatment of contaminated soils may decidedly reduce the percentage of scab if enough sulfur is employed and the moisture and other soil conditions are such that it is able to exert its maximum effect."

The rôle that sulfur plays in the soil is an undecided question. Chancrin and Desriot (4) express the opinion that its beneficial effects may be due to action similar to that of partial sterilization by heat, carbon-bisulfide, toluene, etc. In its use for the control of scab its beneficial action would appear to be due to the fact that on its oxidation there is an increase in soil acidity, thus producing conditions unfavorable for the development of the scab organism. Numerous investigators, among whom might be mentioned Brioux and Guerbet (1), Brown and Kellogg (2) and Lipman and his co-workers (17) have demonstrated that the presence of sulfofying organisms as well as the moisture relations are factors of considerable importance in the oxidation of sulfur. Since it is a well established fact that the biological factor is influential in the process it is possible that some of the reported failures of sulfur applications to control scab may be explained on the ground that the sulfur was not oxidized.

In a series of carefully performed field experiments, Sherbakoff (19) applied sulfur at the rate of 450 and 900 pounds per acre. In every case there was a reduction in the amount of scab, the heavier application giving the greatest decrease. Included in these experiments were tests to determine the influence of the time of application of the sulfur. Most efficient control was secured where the sulfur was broadcasted just before the potatoes were planted. Mixing the sulfur with the fertilizer not only reduced the fungicidal effect of the sulfur but reduced the value of the fertilizer as well. In another paper Sherbakoff (20) reports that where heavy applications of sulfur were made injurious effects were apparent on clover the following year, the injury being in proportion to the amount of sulfur applied.

Lint (16) conducted field experiments with sulfur over a period of three years and found that any quantity over 600 pounds is not to be advised except under especially alkaline conditions. In cases where sulfur was applied at the rate of 600 and 800 pounds per acre in the row, Lint reports injury on the succeeding hay crop. Where smaller amounts were used, and the applications made broadcast the danger of injury was reduced to a minimum.

From the brief review of the previous investigations on the use of sulfur for the control of potato scab, it is apparent that the chief difficulty lies in

determining the amount necessary to change the soil reaction to a degree that will inhibit the growth of the scab organism without interfering with the proper development of the potato crop or of subsequent crops. That the soil acidity may be increased to this extent without injury to the potato crop, is evident from the work of Gillespie and Hurst (8). They have shown that while the Caribou loam soils of Maine are more acid than the Washburn loam soils, the potatoes grown on the former are not only free from scab but give larger yields.

In a recent paper having an important bearing on the question of the eradication of the scab organism from the soil, Gillespie and Hurst (9) show that an excellent correlation exists between the hydrogen-ion concentration and the occurrence of the potato scab organism. They examined a number of potato soils of different origin and type and found that those having a hydrogen-ion concentration as low as 5.2 rarely produced scabby tubers while potatoes grown on soils having higher exponents generally were scabby. Among the samples examined by them were two from the same field, a portion of which was limed in 1906 while the remainder received no lime. The limed portions produced scabby potatoes in 1906 and again in 1917, while the potatoes from the unlimed portion were clean both years. On determining the hydrogen-ion concentration of soil samples from the two sections, it was found that the limed and unlimed portions gave pH values of 5.7 and 5.05, respectively. In another paper Gillespie (7) reports the results of studies made of the viability of a number of strains of the scab organism in culture media adjusted to various hydrogen-ion exponents. He found that in a medium having a pH value of 5.2 growth was slower and generally less vigorous than it was in media having higher pH values. In some instances strains of the organism succeeded in growing well in a medium which had an initial pH value of 4.8 but the growth was accompanied by a decrease in acidity. The writer states that it is doubtful if more than a poor growth can occur at such exponents.

While the results of previous experiments with the use of elemental sulfur for the control of potato scab have been contradictory, the evidence as a whole indicates the possibility of its use in this connection. In view of the fact that potato scab is becoming more and more destructive, it was thought advisable that further research be conducted on this problem. Since the presence or absence of the scab organisms appears to be determined to a large extent by the soil reaction, in the experiments here reported particular attention was given to the relation of the organism to soil acidity as measured by the hydrogen-ion concentration and the relation of the latter to the amount of sulfur applied to the soil.

## EXPERIMENTAL

During the summer of 1919, five field experiments were conducted. These experiments were performed on different soil types including sandy loam, Sassafras loam and Penn loam. In selecting the fields in which the experiments were conducted, care was taken to avoid any marked soil irregularities so that differences arising from soil variations might be reduced to a minimum. As an additional precaution check plots were left between each two treated plots and each treatment was repeated at least three times. The size of the plots in the different experiments varied from  $\frac{1}{4}$  to  $\frac{1}{8}$  acre. Except for the sulfur treatments all the plots of an experiment were treated alike as regards fertilization and cultivation.

Sulfur was used in amounts varying from 300 to 1200 pounds per acre. The sulfur used was the commercial flour sulfur. The applications were made broadcast after the land was harrowed and just before planting. In one of the experiments the sulfur was applied by hand, in two others a lime distributor was employed while in the remaining two the applications were made with a grain drill. The latter method proved the most efficient since the sulfur was thoroughly mixed with the surface soil and a more uniform distribution was secured.

Experiments were conducted with the varieties American Giant and Irish Cobbler. When the potatoes were harvested they were separated into two classes, primes and seconds, the latter including all tubers under  $1\frac{1}{2}$  inches in diameter. The primes were then divided into classes depending on the degree of infection. In grading the primes of the American Giant variety, two classes were made, clean and scabby, the latter including all tubers showing any scab lesions. Three classes were made of the Irish Cobbler primes, namely, clean, salable scabby and unsalable scabby. The last class was made up of all tubers covered with the scab lesions while tubers showing only a moderate infection were designated as salable scabby. In this connection, it must be stated that the percentage of salable scabby tubers in the primes is not a fair index of the actual control of scab since the salable scabby tubers from the check plots showed considerably more scab than those from the treated plots. This is particularly true of the American Giant variety, the primes in the sulfur-treated plots not only showed less scab than those from the check plots but were of a much better color and texture.

Before making the sulfur applications, soil samples were taken in the area to be included in the experiment and the hydrogen-ion concentration of water extracts of the soil samples determined colorometrically, following the work by Clark and Lubs (5) in the preparation of the buffer mixtures, the selection of suitable indicators and general methods of procedure. When the crop was harvested, soil samples were taken in each plot and similar determinations were made. In taking the soil samples borings were made to a depth of  $6\frac{1}{2}$  inches, at intervals of 15 feet. These individual samples were then thoroughly mixed and a sample taken to represent the condition of the plot in question.

In preparing the water extracts of the soil samples to be tested a method was adopted which was essentially the same as that employed by Gillespie and Hurst (9). To 15 gm. of air-dry soil which had been passed through a 1-mm. sieve was added 30 cc. of distilled water in a 100-cc. Erlenmeyer flask. The flask was then shaken 75 times, and allowed to stand for a period of 8 to 12 hours. The supernatant liquid was then drawn off and distributed to test tubes.

The yields per acre as well as the percentage of scabby tubers will be presented in the following tables in which the data given are averages obtained from at least three replications of each treatment and of six check plots. The yields of second-size tubers are included in the tables; however, in view of the fact that the sulfur treatments appeared to have no influence on the number of seconds, they will not be discussed.

#### *Experiments with the Irish Cobbler Variety*

*Experiment I.* The soil on which this experiment was conducted is a sandy loam, typical of one of the best potato-growing sections of New Jersey. In 1912 an application of lime was made at the rate of 1200 pounds per acre; since that time succeeding potato crops have been severely scabbed, a large

TABLE 1  
*Influence of sulfur applications on total yield, per cent of scabby tubers and hydrogen-ion concentration*

TREATMENT	TOTAL YIELD	YIELD OF PRIMES			YIELD OF SECONDS	pH VALUE OF SOIL EXTRACTS
		Salable		Unsalable, scabby		
		Clean	Scabby			
	<i>bushels per acre</i>	<i>bushels per acre</i>	<i>per cent</i>	<i>bushels per acre</i>	<i>bushels per acre</i>	
Check*.....	350.1	163.5	64.6	146.8	39.7	6.03
400 pounds sulfur per acre†....	339.1	265.8	29.4	30.2	42.6	5.20
600 pounds sulfur per acre†....	342.7	283.2	19.4	25.9	33.4	5.07

\* Average of 6 plots.

† Average of 4 plots.

portion of the crop being unsalable in 1919. Soil samples taken before the sulfur applications were made showed a hydrogen-ion exponent of 6.15. In this experiment sulfur was used at the rate of 400 and 600 pounds per acre. Observations made at frequent intervals during the summer on this and the other experiments conducted failed to show any differences in vegetative growth that could be attributed to the sulfur applications.

The effects of the sulfur on total yield and scab control are shown in table 1. It will be seen that there was a slight decrease in yield on the treated plots as compared with the check plots; it is doubtful, however, if these differences

can be attributed to the action of the sulfur, since the decrease was greater for the 400 than for the 600-pound application. With both quantities of sulfur used, there was a marked gain in the number of salable primes with a corresponding decrease in the number of tubers rendered unsalable by scab. In addition to this the per cent of scabby tubers in the salable primes was greatly reduced by the sulfur applications.

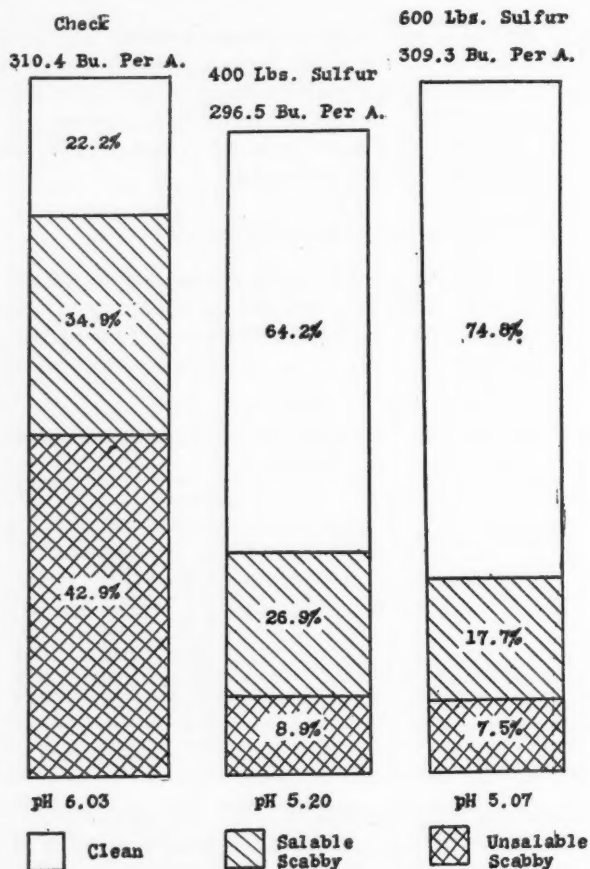


FIG. 1. DIAGRAM SHOWING THE RELATION OF SULFUR TREATMENT TO HYDROGEN-ION CONCENTRATION AND THE PER CENT OF CLEAN, SALABLE AND UNSALABLE SCABBY TUBERS IN THE PRIMES—IRISH COBBLER VARIETY, EXPERIMENT I

The relation of the hydrogen-ion exponent to the per cent of clean, salable scabby and unsalable scabby tubers in the primes is shown in figure 1. The exponent of the check plots when harvested was found to be 6.03; as has

been stated, the original exponent for this soil was 6.15, indicating that little change occurred during the growing season. On the other hand, the plots receiving the sulfur applications showed a decided decrease in exponents, the decrease being more pronounced on the plots receiving the heavier applications. From the diagram it is apparent that with the decrease in the hydrogen-ion exponent there was a corresponding decrease in the per cent of scabby tubers as compared with the check plots. It will be observed, however, that even where the larger quantities of sulfur were used the crop was not entirely free from scab, this despite the fact that the exponent of these plots was 5.07, slightly lower than that shown by Gillespie (7) to delay or inhibit the growth of the scab organism in culture media. This would indicate either that there was not a uniform distribution of the sulfur with the consequence that there was no resulting acidity in those areas not receiving sulfur, or that the organism will grow at lower exponents in soil than in culture media.

*Experiment II.* The soil on which this experiment was conducted is a sandy loam of a heavier type than that on which the first experiment was performed. Scab has been very severe in this field for a number of years. Sulfur was applied at the rate of 300 and 600 pounds per acre.

TABLE 2

*Influence of sulfur on total yield, per cent of scabby tubers and hydrogen-ion concentration*

TREATMENT	TOTAL YIELD	YIELD OF PRIMES			YIELD OF SECONDS	pH VALUES OF SOIL EXTRACTS
		Salable		Unsalable scabby		
		Clean	Scabby			
	<i>bushels per acre</i>	<i>bushels per acre</i>	<i>per cent</i>	<i>bushels per acre</i>	<i>bushels per acre</i>	
Check*.....	174.0	70.4	57.6	85.9	17.7	5.57
300 pounds sulfur per acre†...	181.4	144.6	22.4	24.1	12.7	4.77
600 pounds sulfur per acre†...	171.9	132.0	23.8	22.9	17.1	4.82

\* Average of 6 plots.

† Average of 4 plots.

The results of the sulfur treatments are given in table 2. On a basis of total yield, the plots receiving 300 pounds of sulfur showed an increase as compared with the untreated plots, while the plots treated with 600 pounds of sulfur per acre showed a slight decrease. The differences in either case are small, however, and it is doubtful whether any importance can be attached to them. As in the preceding experiment, there was a marked reduction of unsalable scabby tubers on the treated plots leading to an increase in the number of salable primes. The per cent of scabby tubers in the salable primes was likewise greatly reduced.

In figure 2 is shown the relation of the hydrogen-ion exponent to the per cent of salable and unsalable scabby tubers in the primes. The initial hydrogen-ion exponent of this soil was 5.6 as compared with 5.57 for the check plots at the time of harvesting. It will be seen from the diagram, that the exponent of the plots treated with 300 pounds of sulfur is slightly lower than that of the plots receiving double this amount. This indicates that the sulfur had not all been oxidized at the time of digging. This is corroborated by the work of Shedd (21) who has shown that after about four months the amount of sulfur oxidized was generally about 60 per cent of the total quantity present

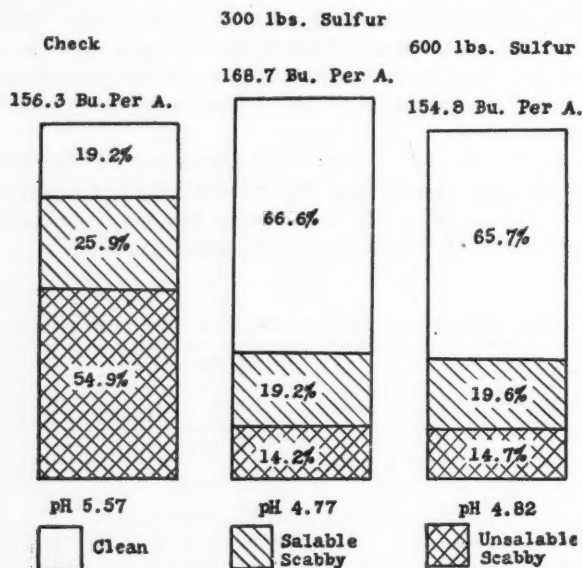


FIG. 2. DIAGRAM SHOWING THE RELATION OF SULFUR TREATMENTS TO HYDROGEN-ION CONCENTRATION AND TO THE PER CENT OF CLEAN, SALABLE AND UNSALABLE SCABBY TUBERS IN THE PRIMES—IRISH COBBLER VARIETY, EXPERIMENT II

regardless of whether 100 or 500 pounds per acre had been added. It will further be seen from the diagram, that scab was approximately as well controlled on the plots receiving 300 pounds of sulfur per acre as it was on the plots where 600 pounds were used. It thus appears from the results of this experiment that, for this particular soil type, having the hydrogen-ion exponent as low as 5.6, the use of sulfur in any quantity exceeding 300 pounds was unnecessary for the control of scab.

*Experiment III.* The soil on which this experiment was conducted is a Penn Loam that had not been planted in potatoes for a number of years. To

insure the presence of the scab organism in the soil scabby seed was planted. Sulfur applications were made at the rate of 300, 600, 900 and 1200 pounds per acre. The results of this experiment are given in table 3.

On the basis of total yield the plots treated with sulfur at the rate of 600 pounds per acre showed a decrease of 9.9 bushels per acre as compared with the check plots. Each of the other plots showed an increase in yield. This increase was 2.7 bushels, 11.9 bushels and 12.3 bushels per acre for the plots treated with 300, 900 and 1200 pounds of sulfur, respectively. In this experi-

TABLE 3

*Influence of sulfur applications on total yield, per cent of scabby tubers and hydrogen-ion concentration*

TREATMENT	TOTAL YIELD	YIELD OF PRIMES		YIELD OF SECONDS	pH VALUES OF SOIL EXTRACTS
		Clean	Scabby		
		bushels per acre	per cent		
Check*	144.3	128.4	60.0	14.7	6.27
300 pounds sulfur per acre†	147.0	135.4	43.6	11.6	5.90
600 pounds sulfur per acre†	134.4	119.4	26.9	15.0	5.83
900 pounds sulfur per acre†	156.2	141.8	26.3	14.1	5.13
1200 pounds sulfur per acre†	156.6	142.5	15.7	14.1	5.10

\* Average of 8 plots.

† Average of 3 plots.

TABLE 4

*Influence of sulfur applications on hydrogen-ion concentration of soil extracts*

TREATMENT	DATE OF SAMPLING								AVERAGE
	5/19	5/29	6/14	6/24	7/18	7/24	8/2	8/16	
	pH	pH	pH	pH	pH	pH	pH	pH	
Check*	6.37	6.43	6.32	6.05	6.23	6.40	6.30	6.27	6.27
300 pounds sulfur per acre†	6.40	6.26	6.00	5.70	6.20	6.00	6.10	5.90	6.07
600 pounds sulfur per acre†	6.13	5.70	5.20	4.93	5.63	5.60	5.53	5.83	5.57
900 pounds sulfur per acre†	5.90	5.16	5.16	4.63	5.90	5.00	5.16	5.13	5.25
1200 pounds sulfur per acre†	5.70	5.43	4.60	4.43	5.10	4.80	4.86	5.10	5.00

\* Average of 8 plots.

† Average of 3 plots.

ment no tubers were rendered unsalable by scab. From table 3 it will be observed that the per cent of scabby tubers in the primes decreased with the increased sulfur applications, the plots receiving the highest sulfur application yielding the lowest per cent of scabby tubers.

Soil samples were taken 35 days after the sulfur applications were made and again approximately every 10 days until the crop was harvested. Water extracts of all the soil samples were made and these were tested for the hydrogen-ion concentration. The results of these tests are given in table 4. It will

be seen that there was no marked variation in the hydrogen-ion exponents of the check plots, if the one indicated for June 24 is excepted, this being the lowest of these values. The mean value of all the determinations was 6.3. The exponents of the treated plots at the time when the first observation was made, with the exception of the one indicated for the plots receiving 300 pounds of sulfur, were lower than were those of the check plots. The values of the hydrogen-ion exponents of the soil extracts corresponding to each of the different treatments show a gradual decline, the lowest of these values for each treatment being indicated for June 24, 71 days after the sulfur applications were made. The hydrogen-ion exponents indicated for dates subsequent to June 24 are somewhat variable and all are slightly higher than are those indicated for this date. No explanation is here offered for the sudden interruption (indicated in table 4 for June 24) in the decline of the values of the

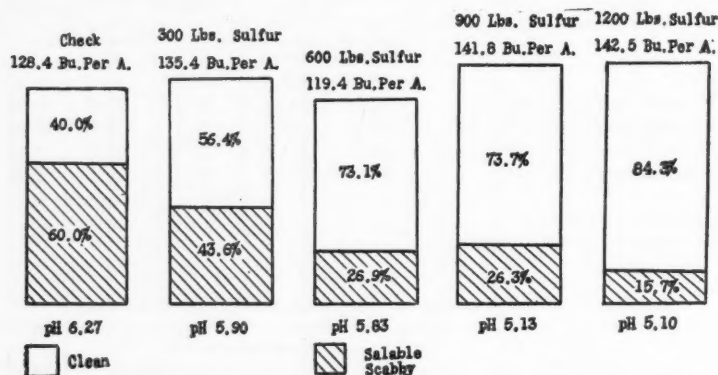


FIG. 3. DIAGRAM SHOWING THE RELATION OF SULFUR TREATMENTS TO HYDROGEN-ION CONCENTRATION AND TO THE PER CENT OF CLEAN AND SALABLE SCABBY TUBERS IN THE PRIMES—IRISH COBBLER VARIETY, EXPERIMENT III

hydrogen-ion exponents. It is suggested, however, that oxidation of the sulfur might have been completed at this time (71 days after application), so that further decrease in the values of the hydrogen-ion exponents of the soil extracts from this cause could not be expected. This suggestion is in accord with the work of Lint (15) who has shown that sulfur is practically completely oxidized in the soil in 8 weeks. On the other hand, it must be recalled that Shedd (21) found that only 60 per cent of the sulfur added to the soil was oxidized after four months.

The relation of the hydrogen-ion exponents to the per cent of scabby tubers is shown in figure 3. It will be observed that the 300-pound application of sulfur reduced the quantity of scabby tubers from 60 per cent (indicated for the check plots) to 43.6 per cent. This is somewhat striking since the average of the hydrogen-ion exponents of the plots receiving the 300-pound

treatment is 6.07, and at no time during the growing season did the exponents for these plots show values lower than 5.7, which is considerably above the highest exponent value found by Gillespie (9) to inhibit growth of the scab organism in culture media.

The per cent of scabby tubers among the primes harvested from the plots treated with 600 pounds and those treated with 900 pounds of sulfur per acre was nearly the same, being 26.9 per cent of the total yield of primes for the former and 26.3 per cent for the latter, as compared with 60 per cent for the check plots. The average values of the hydrogen-ion exponents for the plots which had received the 600-pound treatment and for those which had received the 900-pound treatment were 5.57 and 5.25, respectively. It is to be recalled here that the check plots in the preceding experiments showing average hydrogen-ion exponent values of 5.57 and 6.03 yielded a very high percentage of scabby potatoes. The marked decrease in the per cent of diseased tubers among the primes yielded by the plots treated with 600 pounds of sulfur per acre, in spite of the fact that the average hydrogen-ion exponent for these plots was as high as 5.57, may perhaps be explained upon the ground that at one time during the growing season their hydrogen-ion exponent was as low as 4.93.

The plots receiving the 1200-pound treatment showed the lowest hydrogen-ion exponent values and the lowest per cent (15.7) of scabby tubers among the primes, while the total yield, even with this heavy application of sulfur, was considerably increased in comparison with the corresponding yield from the check plots.

#### *Experiments with the American Giant variety*

*Experiment I.* The soil on which this experiment was conducted is a heavy loam that had produced severely scabbed potatoes the preceding year. Sulfur was applied at the rate of 300 and 400 pounds per acre. The results of the experiment are given in table 5 and in the diagrams of figure 4. On the basis of total yield, the treated plots showed an increase over the untreated check plots, this increase amounting to 20.5 bushels per acre for the 300-pound treatments and 5.8 bushels per acre for the 600-pound treatments. From table 5 it will be seen that the per cent of scabby tubers in the primes was greatly reduced by the sulfur treatments. Of the total yield of primes from the untreated plots 82 per cent were diseased while the plots treated with 300 pounds of sulfur per acre and those receiving the 400-pound treatment gave total yields of primes of which only 23.6 per cent and 15.8 per cent, respectively, were scabby.

The relation of the hydrogen-ion exponents of the soil samples from the plots in this experiment to the per cent of scabby tubers is shown in figure 4. Soil samples taken before the sulfur applications were made gave an average hydrogen-ion exponent value of 5.6. At the time of harvesting, the average

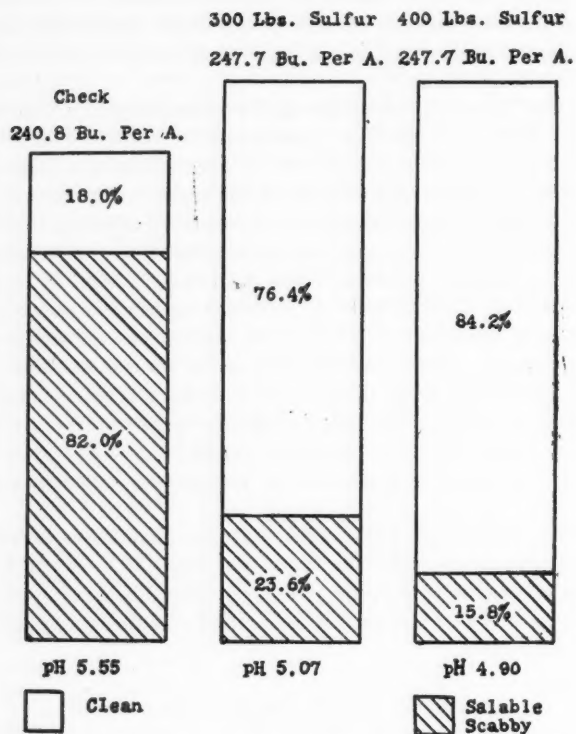


FIG. 4. DIAGRAM SHOWING THE RELATION OF SULFUR TREATMENTS TO HYDROGEN-ION CONCENTRATION AND THE PER CENT OF CLEAN AND SALABLE SCABBY TUBERS IN THE PRIMES—AMERICAN GIANT VARIETY, EXPERIMENT I

TABLE 5

*Influence of sulfur applications on total yield, per cent of scabby tubers and hydrogen-ion concentration*

TREATMENT	TOTAL YIELD	YIELD OF PRIMES		SECONDS	pH VALUES OF SOIL EXTRACTS
		Clean	Scabby		
	<i>bushels per acre</i>	<i>bushels per acre</i>	<i>per cent</i>	<i>bushels per acre</i>	
Check*.....	280.8	240.8	82.0	40.0	5.55
300 pounds sulfur†.....	301.3	247.7	23.6	53.6	5.07
400 pounds sulfur†.....	286.6	247.7	15.8	38.9	4.90

\* Average of 6 plots.

† Average of 4 plots.

hydrogen-ion exponent values of soil samples taken from the check plots was 5.55 while the corresponding exponent values for the samples from the plots treated with 300 pounds and from those treated with 400 pounds of sulfur per acre were 5.07 and 4.90, respectively. It will thus be observed from table 5 and from the diagrams of figure 4 that with each decrease in the value of the hydrogen-ion exponents below that of the check plots, a corresponding decrease occurred in the per cent of scabby tubers among the primes.

*Experiment II.* This experiment was conducted on a light sandy loam soil underlaid at a shallow depth by a greensand marl. In 1918 potatoes grown in the field had been severely scabbed. Sulfur was applied at the rate of 500 and 700 pounds per acre. The results are presented in table 6. The data of this table indicate a reduction of 44.8 bushels per acre for the plots treated with 500 pounds of sulfur in comparison with the corresponding yields from the check plots. It is questionable, however, whether this decrease in yield

TABLE 6  
*Influence of sulfur applications on total yield, per cent of scabby tubers and hydrogen-ion concentration*

TREATMENT	TOTAL YIELD	YIELD OF PRIMES		YIELD OF SECONDS	pH VALUES OF SOIL EXTRACTS
		Clean	Scabby		
	<i>bushels per acre</i>	<i>bushels per acre</i>	<i>per cent</i>	<i>bushels per acre</i>	
Check*.....	247.3	184.4	64.4	62.8	5.6
500 pounds sulfur†.....	202.5	161.2	38.8	41.3	4.8
700 pounds sulfur†.....	250.8	191.6	23.8	59.1	4.8

\* Average of 6 plots.

† Average of 4 plots.

can be ascribed to the sulfur treatment, since the plots receiving the 700-pound application gave an increase of 3.5 bushels per acre over the yields from the check plots. A much lower percentage of scabby tubers was obtained from the treated than from the untreated plots. This decrease in the percentage of scabby tubers was much more pronounced than is apparent from the figures given in the table, since the tubers from the treated plots classified as scabby showed fewer lesions than did those from the check plots.

The relation of the hydrogen-ion exponents of the soil samples collected from the treated and untreated plots to the yields of scabby and clean tubers is shown in the diagrams of figure 5. Soil samples taken before the sulfur applications were made gave an average hydrogen-ion exponent value of 5.8. At the time of harvesting, the average hydrogen-ion exponent values of the soil samples from the check plots treated with 700 pounds and from those treated with 500 pounds of sulfur per acre was 4.8 in both cases. Despite this fact the per cent of scabby tubers among the primes harvested from the plots treated with 700 pounds was lower than from those treated with 500

pounds, being 23.8 for the former and 38.8 for the latter, as compared with 64.4 for the check plots.

In this experiment the amount of scab on the tubers from the treated plots was reduced to only a few lesions. It is doubtful whether scab could be entirely eliminated from the crop even by heavier applications of sulfur, since the exponent values resulting from the 400 and 700-pound applications are considerably lower than the exponent shown by Gillespie (7) to inhibit the growth of the scab organism in culture media.

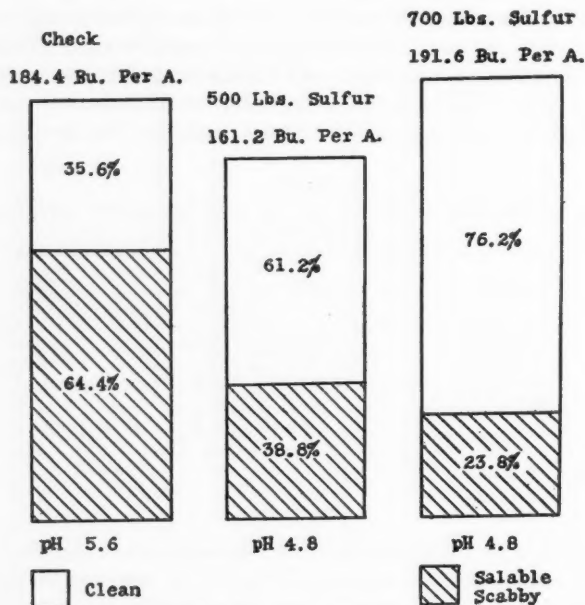


FIG. 5. DIAGRAM SHOWING THE RELATION OF SULFUR TREATMENTS TO HYDROGEN-ION CONCENTRATION AND THE PER CENT OF CLEAN AND SALABLE SCABBY TUBERS IN THE PRIMES—AMERICAN GIANT VARIETY, EXPERIMENT II

The necessity of determining the hydrogen-ion concentration of the soil before making sulfur applications is evident from the experiments here reported. In the case of three of these, soil samples taken before the sulfur applications were made showed an average hydrogen-ion concentration of 5.66. At the time of harvesting the average hydrogen-ion exponent values of the soil samples from plots receiving 300 pounds of sulfur per acre was approximately the same as where larger amounts (400 to 700 pounds) were used, being 4.92 for the former and from 4.8 to 4.9 for the latter. Scab was likewise approximately as well controlled on the plots receiving the 300-pound application as where the heavier applications were made, the percentage of scabby

tubers in the primes being 28.5 for the former and from 15.8 to 38.8 for the latter. In the other two experiments soil samples taken before the sulfur applications were made showed an average exponent value of 6.26, and here the heavier applications of sulfur (400 to 1200 pounds) not only gave a greater decrease in the exponent values than the lighter applications (300 pounds) but with each decrease in the value of the hydrogen-ion exponents below that of the check plots, a corresponding decrease occurred in the per cent of scabby tubers among the primes.

#### SUMMARY

With due regard for the limitations of the experiments here reported, resulting from the fact that they were conducted for one year only, the following points may be advanced.

1. With the different amounts of sulfur used, all gave substantial gains in the number of clean tubers. With the heaviest application, however, scab was not entirely eliminated.
2. The results would indicate that with those varieties of potatoes known to scab severely the use of sulfur in the proper amount will render a large portion of the crop salable.
3. In all cases, following applications of sulfur there was an increase in soil acidity as measured by the hydrogen-ion concentration of soil extracts. In most instances this increase in acidity, corresponding to a decrease in hydrogen-ion exponent, was in proportion to the amount of sulfur applied.
4. With a decrease in hydrogen-ion concentration there was a decrease in the number of scabby tubers.
5. The necessity of knowing the soil reaction before sulfur applications are made is evident from the fact that where the hydrogen-ion concentration of water extracts of soil samples taken before the sulfur applications were made was 5.8 or less, the lighter applications (300 to 500 pounds) gave approximately as good control of scab as the heavier applications (700 to 1200 pounds). Where the initial exponent was greater than 6.0 the heavier applications gave the best control.
6. The results of the present work would indicate that the limiting exponent for the growth of the scab organism is lower in soil than in culture media.

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# EFFECT OF VARIOUS SOLUBLE SALTS AND LIME ON EVAPORATION, CAPILLARY RISE, AND DISTRIBUTION OF WATER IN SOME AGRICULTURAL SOILS

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## INTRODUCTION

Soil fertility can not be maintained if crops are removed from the land and not enough of the plant-food is returned to the soil to compensate it for the loss. In spite of some contentions to the contrary, it can not even be maintained, if a strictly live-stock type of farming is practiced, in which all crops are fed to the farm animals and manure is carefully preserved and returned to the soil. If animals themselves or animal products, such as milk, cheese, wool, eggs, etc., are removed from the farm, a considerable amount of soil fertility is carried away. As a general rule, the barnyard manure is not carefully conserved on American farms, and before it reaches the field more or less of the plant-food is lost through ammonification, leaching, etc. Moreover, there is a considerable loss of plant-food from soil in the drainage water through washing during excessive rains and leaching. If we are to preserve the present status of soil fertility, therefore, we must in some way periodically compensate soil for the constant loss in its fertility. This being established, it implies that such compensation on a national scale must be largely in the form of the application of some chemical fertilizers, the nature of which might vary considerably, depending on the character of the soil, climatic conditions, and the systems and methods of farming.

Regardless of the nature and the kind of fertilizer materials to be used most advantageously under different conditions, it is of considerable importance that the question of the effect of these materials on some soil properties should be studied.

Soil moisture is one of the most important factors in crop production. Broadly speaking, the conservation of soil moisture in order to have an ample water supply at the proper time for the germination of seed, growth and development of crops is a subject of much study and consideration among the agriculturists of to-day. The present study was undertaken with the hope of obtaining some additional information on the subject of the effect of some chemical substances on evaporation, capillary rise and distribution of water in some agricultural soils.

REVIEW OF LITERATURE ON THE EFFECT OF SOLUBLE SALTS ON EVAPORATION  
OF SOIL MOISTURE

There are several men who have contributed to our knowledge on the general subject of the effect of chemical compounds on the evaporation of water from soils.

Warrington (18), in his book on "Physical Properties of Soils," cited Johnson and Armsby of Connecticut and King of Wisconsin, who did some work along this line. They found that "saline matter of the soil, or of additions of saline manures" very materially decreases the evaporation of soil water. The action of these materials was attributed to the fact that a slight crust was formed on the surface and completely filled up the interstices of soil. "From this point of view," adds Warrington (18, p. 118), "salts of little solubility, as gypsum, should be those which most effectively hinder evaporation."

Buffum (5) in studying alkali soils of Wyoming, was impressed with the fact that all alkali soils appear damp, when adjoining lands may be almost perfectly dry. Thinking that the salts of alkali lands prevented the loss of water, he treated some normal soil in pots with solutions of various concentrations of sodium chloride, sodium carbonate, sodium sulfate, magnesium sulfate and sugar. He found that every one of these substances diminishes the evaporation, and that their effect is increased with the concentration. When about 2.2 per cent of alkali salts were present in soil, the evaporation of water from the soil decreased to about one-half, as compared with the untreated soil.

Briggs (2), working with sodium chloride, sodium carbonate and sodium sulfate, substantiated Buffum's results. Explaining the effect of soluble salts on the evaporation of soil water, he presented an excellent discussion on the rôle of surface tension, viscosity and vapor pressure as contributing to the results found. Since his quantitative results and also those of Buffum's experiments considerably exceeded those that could be justified from theoretical consideration of the three factors mentioned above, Briggs attributed them to the crystallization of salts at the surface, thus forming a mulch.

Mohr (16), in 1909, studying the rate of evaporation from water and soil surfaces, had noticed that at the beginning evaporation was greater from the soil, but later decreased until it was less than from the water surface. It would seem that this change in the rate of evaporation in case of soil might be due to the effect of soluble salts in that soil. When their amount became large enough at the surface to modify considerably the concentration of the soil solution, its effect on the rate of evaporation became pronounced.

Dumus (7) in 1911 studied the effect of some salts on evaporation of water from soil in tumblers. His results show that soluble salts decrease the evaporation.

More recently Harris and Robinson (8) have tested the effect of a solution of sodium chloride on quartz sand in small porcelain crucibles. The salt concentration was varied from half normal to 7 times normal. The evapo-

ration was allowed to take place under a bell jar in order to avoid air currents. The results show that with the increase in concentration of sodium chloride the evaporation gradually decreased.

This brief perusal of some of the available literature on the subject shows very clearly that the soluble and insoluble salts affect to some extent the rate at which water evaporates from the soil. However, the data are not available on this subject that would tend to show how lime and some of the soluble salts which are often used in agricultural practice would influence the rate of water evaporation from some agricultural soils, when water is supplied and constantly brought from a given depth below the soil surface. Also, what relation, if any, exists between evaporation of soil water, capillary rise and eventual distribution of soil water as influenced by these chemical substances? In the present study an endeavor is made to add some data on this subject.

#### EFFECT OF DIFFERENT CHEMICAL SUBSTANCES ON EVAPORATION OF WATER FROM DIFFERENT SOILS

##### *Procedure*

In the present work only chemically pure substances were used for treating the soils.

After some preliminary trials it was decided to adhere to the following general procedure. Cylinders, 12 inches long and 4 inches in diameter, with the bottoms made of wire gauze, were filled uniformly and with considerable packing, with sand or an air-dried soil. Then the surface three inches of the soil was removed and thoroughly mixed with 7.6 gm. of a given salt or lime, and the soil was packed back into the cylinder. Since the surface of the exposed area in the cylinders equals 12.566 square inches, the application of 7.6 gm. of chemical substance represents approximately 1 ton to the acre. To prevent any chemical action of soil solution on the galvanized iron of the cylinders, the inner walls of the cylinders were carefully coated with melted paraffine before filling in the soil. The cylinders containing the soil, when placed in their special bases, formed units similar to evaporimeters made by the Central Scientific Company of Chicago. Distilled water was supplied from these base containers which served as reservoirs, thus keeping the base of the soil column always moist. The whole apparatus was weighed from time to time, usually every other day. Livingston's (15) porous cup atmometer was set up among the soil evaporimeters and the evaporation of water from this atmometer was observed during the period of experiments. The evaporimeters were placed in a greenhouse and the evaporation continued from 35 to 50 days.

##### *Results and discussion*

The results with sea sand, Sassafras medium sandy loam, Penn loam, Elkton clay loam, and muck, treated with ammonium sulfate, potassium

sulfate, magnesium sulfate, sodium chloride, calcium nitrate, potassium diphosphate and calcium oxide, are given in tables 1, 2, 3, 4, and 5 and summarized graphically in figure 1. Later, when larger cylinders were set up for determining the effect of the application of sodium chloride, potassium monophosphate and calcium oxide on the moisture content of brown silt loam,

TABLE 1  
*Effect of different salts and lime on the evaporation of water from sea sand*  
Experiment continued 37 days

TREATMENT	CYLINDER		AVERAGE	DECREASE OVER UNTREATED	WATER SAVED BY TREATMENT
	1	2			
	gm.	gm.	gm.	gm.	per cent
Untreated.....	313	355	334		
(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub> .....	113	105	109	225	65.7
K <sub>2</sub> SO <sub>4</sub> .....	132	138	135	199	59.6
MgSO <sub>4</sub> .....	190	239	215	119	35.7
NaCl.....	94	156	125	209	62.6
Ca(NO <sub>3</sub> ) <sub>2</sub> .....	93	96	95	239	71.6
KH <sub>2</sub> PO <sub>4</sub> .....	114	108	111	223	66.8
CaO.....	215	316	266	68	20.3
Atometer.....			656		

TABLE 2  
*Effect of different salts and lime on evaporation of water from Sassafras medium sandy loam*  
Experiment continued 50 days

TREATMENT	CYLINDER		AVERAGE	DECREASE OVER UNTREATED	WATER SAVED BY TREATMENT
	1	2			
	gm.	gm.	gm.	gm.	per cent
Untreated.....	641	610	626		
(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub> .....	477	482	480	146	23.32
K <sub>2</sub> SO <sub>4</sub> .....	555	558	557	69	11.02
MgSO <sub>4</sub> .....	476	495	486	140	22.37
NaCl.....	397	388	393	233	37.22
Ca(NO <sub>3</sub> ) <sub>2</sub> .....	422	428	425	201	32.11
KH <sub>2</sub> PO <sub>4</sub> .....	611	548	580	46	7.35
CaO.....	628	579	604	22	3.51
Atometer.....			708		

additional data on the influence of these substances on the evaporation of water from soil were obtained. These figures, comprising an observation of a 10-day period, are given in table 6.

The results with different soils and chemicals show several interesting features. When the applications are made in the amounts used in these experiments all the above-mentioned soluble salts and the base decrease the rate of evaporation of water from the soils studied. Their effect, however,

varies considerably with different soils. Generally speaking, the influence of soluble salts is most pronounced in the sea sand and least pronounced in the Penn loam. Also the depressing effect is greater in the Elkton clay loam than in the Sassafras sandy loam. Likewise, the behavior of some individual substances with different soils is worth noticing. Sodium chloride, for ex-

TABLE 3  
*Effect of different salts and lime on the evaporation of water from Penn loam*  
Experiment continued 41 days

TREATMENT	CYLINDER		AVERAGE	DECREASE OVER UNTREATED	WATER SAVED BY TREATMENT
	1	2			
	gm.	gm.	gm.	gm.	per cent
Untreated.....	966	953	960		
(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub> .....	734	751	743	217	22.6
K <sub>2</sub> SO <sub>4</sub> .....	867	832	850	110	11.5
MgSO <sub>4</sub> .....	789	780	785	175	18.2
NaCl.....	761	741	751	209	21.8
Ca(NO <sub>3</sub> ) <sub>2</sub> .....	802	779	791	169	17.6
KH <sub>2</sub> PO <sub>4</sub> .....	902	888	895	65	6.8
CaO.....	841	875	858	102	10.6
Atmometer.....			697		

TABLE 4  
*Effect of different salts and lime on the evaporation of water from Elkton clay loam*  
Experiment continued 35 days

TREATMENT	CYLINDER		AVERAGE	DECREASE OVER UNTREATED	WATER SAVED BY TREATMENT
	1	2			
	gm.	gm.	gm.	gm.	per cent
Untreated.....	917	882	900		
(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub> .....	542	638	590	310	34.4
K <sub>2</sub> SO <sub>4</sub> .....	590	698	644	256	28.4
MgSO <sub>4</sub> .....	570	576	573	327	36.3
NaCl.....	383	385	384	516	57.3
Ca(NO <sub>3</sub> ) <sub>2</sub> .....	441	467	454	446	49.6
KH <sub>2</sub> PO <sub>4</sub> .....	485	629	557	343	38.1
CaO.....	232	343	288	612	68.0
Atmometer.....			590		

ample, is among the most effective in checking the evaporation of water from nearly every soil studied, while potassium sulfate and potassium phosphate could be ranked as among the least effective. Ammonium sulfate and magnesium sulfate occupy rather an intermediate position in this respect. The action of lime is especially interesting. With sand, sandy loam and Penn loam, calcium oxide in the amount applied is one of the least effective; its effect on muck is relatively much more pronounced, while in clay loam it is

the most efficient in decreasing the evaporation of water, as compared with the salts studied.

The relative rate of evaporation of moisture in the lime and salt treated soils can be studied in figure 1 and also figure 4. In the latter figure, in which ammonium sulfate, sodium chloride, and calcium oxide were compared in sandy loam and clay loam, the relative position of soils treated with different substances is worthy of consideration. In comparison with the untreated

TABLE 5  
*Effect of different salts and lime on the evaporation of water from muck*  
Experiment continued 41 days

TREATMENT	CYLINDER		AVERAGE	DECREASE OVER UNTREATED	WATER SAVED BY TREATMENT
	1	2			
	gm.	gm.	gm.	gm.	per cent
Untreated.....	1014	900	957		
(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub> .....	765	767	766	191	20.0
K <sub>2</sub> SO <sub>4</sub> .....	888	921	905	52	5.4
MgSO <sub>4</sub> .....	896	801	849	108	11.3
NaCl.....	437	318	378	579	60.5
Ca(NO <sub>3</sub> ) <sub>2</sub> .....	486	562	524	433	45.5
KH <sub>2</sub> PO <sub>4</sub> .....	672	698	685	272	28.8
CaO.....	612	533	573	384	40.3
Atmometer.....			567		

TABLE 6  
*Effect of different chemical substances on evaporation of water from brown silt loam; data represent grams of water evaporated from cylinders in 10 days and the amount and per cent of water saved by each treatment*

TREATMENT	CYLINDER		AVERAGE	DECREASE DUE TO TREATMENT	
	1	2			
	gm.	gm.	gm.	gm.	per cent
Untreated.....	577	618	598		
NaCl.....	390	398	394	204	34.11
K <sub>2</sub> HPO <sub>4</sub> .....	558	554	556	42	7.02
CaO.....	507	551	529	69	11.54

soil, ammonium sulfate and sodium chloride occupy the same general position in relation to one another. The curve of the limed sandy soil, however, runs next to the curve of the untreated soil, while the curve of the limed clay loam drops to the lowest place. The respective data for soils treated with potassium phosphate (see tables 15 and 16) also show a pronounced difference. In clay loam the effect of this salt is equal to that of ammonium sulfate, while in sandy loam its effect is considerably smaller than that of the latter salt.

In connection with the results obtained the inquiry naturally arises as to why different chemical substances act so differently, when applied to the same soil, and why the behavior of lime, as well as that of potassium phosphate, is apparently different in different soils.

In the attempt to answer the general inquiry several factors must be considered as the agencies contributing to the variations in the effect of different chemical substances on various soils studied.

With an increase in the concentration of the salt solution the vapor pressure is decreased. This well known fact of physical chemistry is of prime importance in understanding the effect of soluble salts on the evaporation of water from soils, for the vapor pressure is defined by a physical chemist as the "tendency shown by the substances to pass from the liquid or solid into the gaseous state," i.e., for evaporation of water from solution or soil surface. It is logical to suppose that this general law is applicable to soil solutions with some possible modifications brought about by any physical or chemical changes in soil due to the introduction of these chemical substances to the soil.

Again, different salts of the same absolute concentration vary considerably in their property to decrease the vapor pressure of the resultant solution. Some of the salts studied in the present work have, according to Tammann (17), the following order of their efficiency in this respect:  $\text{NaCl} > (\text{NH}_4)_2\text{SO}_4 > \text{K}_2\text{SO}_4 > \text{KH}_2\text{PO}_4 > \text{MgSO}_4$ . For the lack of more direct data bearing on the subject studied, this general fact might be helpful in understanding the results obtained on the evaporation of water from soils treated with these salts.

When a given soluble salt, or a solution of this salt, is added to the soil, the concentration of soil solution is increased. The extent of the increase in concentration of soil solution varies very greatly, depending on the salt or the texture of the soil. Bouyoucos and McCool (1), using 0.1N solutions of different salts with different soils have shown that efficiency in increasing the concentration of the soil solution was greater in light sandy soils and decreased with the heavier types of soil. For the individual salts the efficiency followed generally the following order, with the salts studied in the present work:  $\text{Ca}(\text{NO}_3)_2 > (\text{NH}_4)_2\text{SO}_4 > \text{MgSO}_4 > \text{K}_2\text{SO}_4 > \text{K}_2\text{HPO}_4$ . The difference between magnesium sulfate and potassium sulfate is not so striking, while the relative gradation from calcium nitrate to potassium phosphate is very pronounced. Referring again to tables 1, 2, 3, 4 and 5, or to the graphical representation in figure 1, one observes that the order of efficiency in depressing the water evaporation in soils for the salts mentioned above is very similar to the order of their efficiency in increasing the concentration of the soil solution, if added in solutions of 0.1N concentration. In Sassafras sandy loam and muck this order is calcium nitrate > ammonium sulfate > magnesium sulfate > potassium sulfate > potassium phosphate. In Elkton clay loam ammonium sulfate changes places with magnesium sulfate; the remaining salts retain their position. In

sea sand magnesium sulfate is less effective than potassium sulfate, the positions of the remaining salts being unchanged.

#### DISTRIBUTION OF SOLUBLE SALTS IN TREATED SOILS

The relation of the effect of different salts on water evaporation in our experiments could not be expected to be entirely parallel with the effect of these salts on the concentration of soil solution, when applied in concentrations equal to 0.1*N*, because the rate of application in our experiment was widely different from that in Bouyoucos and McCool's experiment. Yet, the parallel is very striking.

In order to verify this important fact, the concentration of the soil solution at different depths of the soil cylinders was determined with the use of the freezing-point method (1). Determinations were made at the end of the experiment, adhering to the following general procedure.

#### *Procedure*

The soil from one of the two cylinders of each treatment was taken out in 1-inch layers down to 6 inches, air-dried, and to a given sample of soil enough water was added to make it into a conveniently workable mud ball. For a given soil the ratio of soil to water remained constant. For the sea sand 25 gm. of sand and 4 cc. of distilled water were used; for Elkton clay loam 20 gm. of soil and 6 cc. of water; for Penn loam, 20 gm. of soil and 6.5 cc. of water; and 10 gm. of muck was mixed with 10 cc. of water. These quantities of prepared material were placed in glass tubes, and freezing-point determinations were made. The soil in the second of the two cylinders of each treatment was flushed with 2 inches of distilled water (412 cc. per 12.566 square inches of the exposed surface of the soil) and allowed to drain; likewise, 1-inch layers of soil were taken out, dried and the concentrations of the soil solution determined by the same method. After every two or three duplicate samples of soil the freezing-point determination of distilled water was made.

#### *Results and discussion*

The results are recorded in tables 7, 8, 9 and 10, an examination of which reveals a very interesting relation of the effect of different substances on the evaporation of water from soils. Remembering that all these substances were applied to the upper 3 inches of the soil, the data show that at the end of the experiment most of the salts were brought to the surface and there deposited. It may be mentioned in passing that the results show that practically no diffusion of salts took place downward against the rise of capillary water. Sodium chloride affords an exception in both sand (in the fourth inch) and muck (fourth and fifth inches), where slight diffusion evidently took place during the 37 days of the duration of the experiment.

If we will consider the osmotic concentrations of the soil solution in the surface inch of soil of the unleached cylinder for different substances, as illustrated in figure 2, and compare the order of the magnitudes of these concen-

TABLE 7

*Concentration of soil solution of sea sand at different depths in the evaporimeters at the end of experiment*

The determinations were made both before and after leaching the sand with 2 inches of water; data represent average of two determinations; 25 gm. of sand and 4 cc. of distilled water mixed together for the test

TREATMENT	DEPTH FROM SURFACE											
	1 inch		2 inches		3 inches		4 inches		5 inches		6 inches	
	Freezing-point depression	Osmotic pressure	Freezing-point depression	Osmotic pressure	Freezing-point depression	Osmotic pressure	Freezing-point depression	Osmotic pressure	Freezing-point depression	Osmotic pressure	Freezing-point depression	Osmotic pressure
	°C.	atm.	°C.	atm.	°C.	atm.	°C.	atm.	°C.	atm.	°C.	atm.
Untreated												
Unleached . . .	0.030	0.36	0.006	0.07	0.007	0.08	0.011	0.13	0.010	0.12	0.007	0.08
Leached . . . .	0.006	0.07	0.008	0.10	0.008	0.10	0.011	0.13	0.011	0.13	0.011	0.13
(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>												
Unleached . . .	2.030	24.40	0.071	0.86	0.061	0.74	0.034	0.41	0.019	0.23	0.016	0.19
Leached . . . .	0.349	4.21	0.136	1.53	0.103	1.24	0.083	1.00	0.080	0.97	0.076	0.92
K <sub>2</sub> SO <sub>4</sub>												
Unleached . . .	1.830	22.00	0.075	0.90	0.030	0.36	0.017	0.20	0.015	0.18	0.015	0.18
Leached . . . .	0.160	1.93	0.045	0.54	0.046	0.55	0.044	0.53	0.046	0.55	0.045*	0.54
MgSO <sub>4</sub>												
Unleached . . .	1.226	14.75	0.012	0.15	0.011	0.13	0.066	0.07	0.004	0.05	0.003	0.04
Leached . . . .	0.410	0.49	0.041	0.49	0.042	0.51	0.040	0.48	0.040	0.48	0.038	0.46
NaCl												
Unleached . . .	2.582	31.00	0.398	4.80	0.088	1.06	0.031	0.37	0.004	0.05	0.005	0.06
Leached . . . .	1.684	20.25	0.167	2.01	0.141	1.70	0.158	1.91	0.177	2.13	0.173	2.09
Ca(NO <sub>3</sub> ) <sub>2</sub>												
Unleached . . .	2.808	33.70	0.301	3.63	0.021	0.25	0.017	0.20	0.014	0.17	0.010	0.12
Leached . . . .	0.194	2.34	0.098	1.18	0.096	1.16	0.088	1.06	0.063	0.76	0.045	0.54
K <sub>2</sub> HPO <sub>4</sub>												
Unleached . . .	1.797	21.30	0.058	0.70	0.022	0.27	0.009	0.11	0.009	0.11	0.011	0.13
Leached . . . .	0.168	2.03	0.089	1.07	0.068	0.82	0.055	0.66	0.052	0.63	0.056	0.68
CaO												
Unleached . . .	0.082	0.99	0.021	0.25	0.010	0.12	0.011	0.13	0.006	0.07	0.009	0.11
Leached . . . .	0.050	0.60	0.041	0.49	0.036	0.43	0.037	0.45	0.031	0.37	0.022	0.27

\* One determination.

trations with the depressive effect of different substances on the evaporation of water from the same soil, we find that these values run in parallel fairly well.

For the sake of simplicity let us temporarily exclude from discussion potassium phosphate and lime. Then in sea sand the order of magnitude of osmotic

concentrations for the different treatments is calcium nitrate > sodium chloride > ammonium sulfate > potassium sulfate > magnesium sulfate, and this is exactly the order of depressive effect of these salts on evaporation (fig. 1). For Elkton clay loam and muck the order for osmotic concentrations is sodium chlor-

TABLE 8

*Concentration of Elkton clay loam at different depths in the evaporimeters at the end of experiment*

The determinations were made both before and after leaching the soil with 2 inches of water; data represent average of two determinations; 20 gm. soil and 6 cc. of distilled water mixed together for the test

TREATMENT	DEPTH FROM SURFACE											
	1 inch		2 inches		3 inches		4 inches		5 inches		6 inches	
	Freezing-point depression	Osmotic pressure	Freezing-point depression	Osmotic pressure	Freezing-point depression	Osmotic pressure	Freezing-point depression	Osmotic pressure	Freezing-point depression	Osmotic pressure	Freezing-point depression	Osmotic pressure
	°C.	atm.	°C.	atm.	°C.	atm.	°C.	atm.	°C.	atm.	°C.	atm.
Untreated												
Unleached....	0.156	1.88	0.020	0.24	0.018	0.21	0.019	0.23	0.018	0.22	0.018	0.22
Leached.....	0.114	1.38	0.032	0.39	0.028	0.34	0.020	0.24	0.021	0.25	0.020	0.24
(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>												
Unleached....	1.323	15.92	0.086	1.04	0.051	0.62	0.046	0.55	0.014	0.17	0.013	0.16
Leached.....	0.634	7.64	0.239	2.88	0.164	1.98	0.134	1.51	0.101	1.22	0.037	0.45
K <sub>2</sub> SO <sub>4</sub>												
Unleached....	0.897	10.80	0.052	0.63	0.025	0.30	0.022	0.27	0.017	0.20	0.017	0.20
Leached.....	0.509	6.13	0.094	1.13	0.097	1.17	0.056	0.68	0.058	0.70	0.057	0.69
MgSO <sub>4</sub>												
Unleached....	0.449	5.41	0.049	0.59	0.038	0.46	0.020	0.24	0.019	0.23	0.018	0.22
Leached.....	0.102	1.23	0.086	1.04	0.136	1.53	0.133	1.49	0.080	0.97	0.073	0.88
NaCl												
Unleached....	4.043	48.60	0.161	1.94	0.067	0.81	0.026	0.31	0.022	0.27	0.016	0.19
Leached.....	2.152	24.76	0.599	7.22	0.137	3.82	0.263	3.17	0.260	3.13	0.235	2.83
Ca(NO <sub>3</sub> ) <sub>2</sub>												
Unleached....	2.094	25.16	0.055	0.66	0.029	0.35	0.021	0.25	0.021	0.25	0.021	0.25
Leached.....	1.200	14.44	0.284	3.42	0.232	2.80	0.172	2.07	0.142	1.71	0.119	1.44
K <sub>2</sub> HPO <sub>4</sub>												
Unleached....	0.238	2.87	0.043	0.52	0.020	0.24	0.011	0.13	0.009	0.11	0.010	0.12
Leached.....	0.162	1.95	0.062	0.75	0.035	0.42	0.029	0.35	0.029	0.35	0.025	0.30
CaO												
Unleached....	0.114	1.38	0.034	0.41	0.033	0.40	0.014	0.17	0.014	0.17	0.013	0.16
Leached.....	0.066	0.80	0.053	0.64	0.051	0.62	0.045	0.54	0.046	0.55	0.038	0.46

ide > calcium nitrate > ammonium sulfate > potassium sulfate > magnesium sulfate. The order of their effectiveness in retarding the evaporation is also the same with the exception of magnesium sulfate. The latter salt in clay and muck soils in this respect is more effective than potassium sulfate. This fact, moreover, is brought out by every soil studied (fig. 1), sand being an

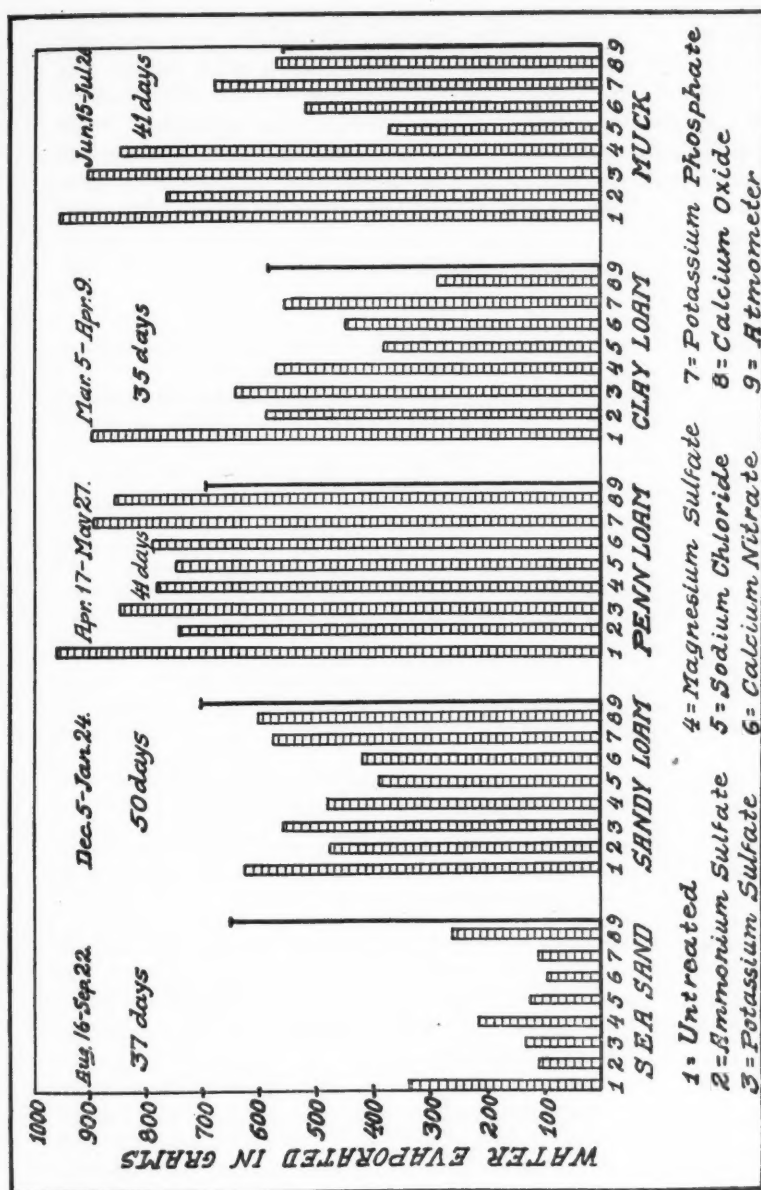


FIG. 1. INFLUENCE OF VARIOUS SALTS AND LIME ON THE EVAPORATION OF WATER FROM DIFFERENT SOILS AND SAND

The dates show the time of the year when the experiment was conducted and its duration. With the exception of no. 9, which represents the atmometer, the numbers correspond to those on the soil cylinders with the various treatments.

exception. Perhaps the behavior of this salt is due to its effect on the physical properties of soils studied. In sand the salts probably were practically unchanged (with the exception of ammonium sulfate, which perhaps was partly nitrified). In the soils, however, some reactions took place, such as double decomposition, exchange of bases, absorption and adsorption. Some of these reactions, undoubtedly, have very considerably modified the soil solution qualitatively; they also affected the physical conditions of the soils. This latter effect is also somewhat noticeable in the case of potassium phosphate and especially in that of calcium oxide. Only in sea sand the applied potassium phosphate retained a considerable concentration of the soil solu-

TABLE 9

*Concentration of soil solution of Penn loam at different depths in evaporimeters at the end of experiment*

The determinations were made both before and after leaching the soil with 2 inches of water; data represent average of two determinations; 20 gm. of soil and 6½ cc. of distilled water mixed together for the test

TREATMENT	DEPTH FROM SURFACE											
	1 inch		2 inches		3 inches		4 inches		5 inches		6 inches	
	Freezing-point depression	Osmotic pressure	Freezing-point depression	Osmotic pressure	Freezing-point depression	Osmotic pressure	Freezing-point depression	Osmotic pressure	Freezing-point depression	Osmotic pressure	Freezing-point depression	Osmotic pressure
Untreated	°C.	atm.	°C.	atm.	°C.	atm.	°C.	atm.	°C.	atm.	°C.	atm.
Unleached....	0.151	1.82	0.018	0.22	0.014	0.17	0.009	0.11	0.008	0.10	0.008	0.10
Leached.....	0.130	1.46	0.027	0.33	0.016	0.19	0.005	0.06	0.006	0.07	0.008	0.10
(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>												
Unleached....	1.691	20.33	0.143	1.72	0.043	0.52	0.009	0.11	0.011	0.13	0.010	0.12
Leached.....	0.615	7.41	0.232	2.80	0.116	1.40			0.064	0.77		
CaO												
Unleached....	0.099	1.19	0.023	0.28	0.019	0.23	0.019	0.23	0.018	0.22	0.016	0.19
Leached.....	0.057	0.69	0.033	0.40	0.019	0.23			0.016	0.19	0.016	0.19

tion. In both Elkton clay loam and muck the soil solution with this salt showed a very slight increase in concentration over the untreated soil. The decrease in evaporation of water due to this salt was unproportionally large, as one would notice by comparing the data in figures 1 and 2 for potassium sulfate and potassium phosphate.

If we are going to apply the same criterion in the study of the behavior of calcium oxide, the results obtained are still more striking. The concentration of the soil solution of soils or sand treated with this substance is very small, in all three soils studied it was even slightly lower than the concentration of the soil solution in the untreated cylinder. Its effect on evaporation is slight in sandy loam, larger in Penn loam, still greater in muck, and was

very great indeed in Elkton clay loam. In this latter soil its influence was greater than that of any other salt tried. There is a very strong possibility that the effect of calcium oxide on the change in physical condition of the clay soil was responsible for such enormous decrease in the evaporated water.

TABLE 10

*Concentration of soil solution of muck at different depths in the evaporation at the end of experiment*

The determinations were made both before and after leaching the sand with 2 inches of water; data represent average of two determinations; 10 gm. of muck and 10 cc. of distilled water used for the test

TREATMENT	DEPTH FROM SURFACE											
	1 inch		2 inches		3 inches		4 inches		5 inches		6 inches	
	Freezing-point depression	Osmotic pressure	Freezing-point depression	Osmotic pressure	Freezing-point depression	Osmotic pressure	Freezing-point depression	Osmotic pressure	Freezing-point depression	Osmotic pressure	Freezing-point depression	Osmotic pressure
Untreated	°C.	atm.	°C.	atm.	°C.	atm.	°C.	atm.	°C.	atm.	°C.	atm.
Unleached....	0.230	2.77	0.061	0.74	0.060	0.72	0.063	0.76	0.062	0.75	0.062	0.75
Leached.....	0.140	1.69	0.141	1.70	0.088	1.06	0.045	0.54	0.035	0.42	0.034	0.41
(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>												
Unleached....	0.824	8.92	0.255	3.07	0.121	1.46	0.080	0.97	0.064	0.77	0.060	0.72
Leached.....	0.367	4.42	0.448	5.40	0.297	3.58	0.110	1.33	0.046	0.55	0.038	0.46
K <sub>2</sub> SO <sub>4</sub>												
Unleached....	0.568	6.84	0.109	1.32	0.074	0.89	0.074	0.89	0.068	0.82	0.067	0.81
Leached.....	0.236	2.84	0.290	3.50	0.219	2.64	0.160	1.93	0.094	1.13	0.055	0.66
MgSO <sub>4</sub>												
Unleached....	0.269	3.24	0.083	1.00	0.082	0.99	0.076	0.92	0.065	0.78	0.057	0.69
Leached.....	0.131	1.47	0.133	1.49	0.132	1.48	0.093	1.12	0.057	0.69	0.040	0.48
NaCl												
Unleached....	2.242	26.93	0.957	11.52	0.406	4.89	0.218	2.63	0.106	1.28	0.054	0.65
Leached.....	0.225	2.71	0.592	7.13	1.064	12.81	0.935	11.26	0.708	8.53	0.435	5.24
Ca(NO <sub>3</sub> ) <sub>2</sub>												
Unleached....	1.358	16.34	0.124	1.50	0.075	0.90	0.068	0.82	0.068	0.82	0.066	0.80
Leached.....	0.388	4.68	0.680	8.19	0.455	5.48	0.150	1.81	0.054	0.65	0.054	0.65
K <sub>2</sub> HPO <sub>4</sub>												
Unleached....	0.286	3.45	0.092	1.11	0.069	0.83	0.070	0.84	0.066	0.80	0.068	0.82
Leached.....	0.101	1.22	0.144	1.73	0.113	1.36	0.096	1.16	0.061	0.74	0.050	0.60
CaO												
Unleached....	0.180	2.17	0.056	0.68	0.054	0.65	0.062	0.75	0.058	0.70	0.055	0.66
Leached.....	0.080	0.97	0.090	1.09	0.091	1.10	0.062	0.75	0.062	0.75	0.040	0.48

Further, in connection with the results on the determination of solution concentrations in the different soils (tables 7, 8, 9 and 10) it might be mentioned that the salts are fairly well washed down with the 2 inches of water. Even in Elkton clay loam these salts in all cases go down farther than 6 inches.

## EFFECT OF CHEMICAL SUBSTANCES ON THE CAPILLARY RISE OF WATER IN SOILS

Besides the physico-chemical phenomena of the resultant soil solution being responsible for the observed behavior of these substances in checking the evaporation of water from soils, there should be mentioned another factor that might influence the evaporation of water. As it was pointed out previously, the substances were mixed in the 3-inch layer of the soil. Thus the water had to pass through the soil with these different substances before reaching the surface. It is possible, therefore, that their influence on the capillary rise of water was partly responsible for their final effect on the evaporation.

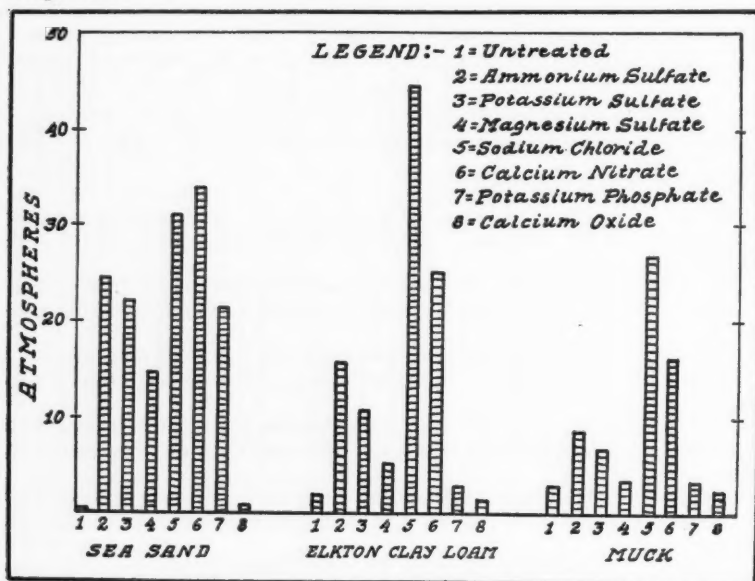


FIG. 2. OSMOTIC CONCENTRATION OF THE SOIL SOLUTION OF THE SURFACE INCH OF DIFFERENT SOILS IN CYLINDERS UNDER VARIOUS SALT TREATMENTS

### Review of literature

The effect of chemical substances on the capillary rise of water in soil has been studied by several investigators. Wollny (20) found that salts which are most readily adsorbed by soils produce little effect on the capillary movement of water, while non-adsorbed salts cause a depression in capillarity, the effect being increased with the concentration.

Kravkov (14), using solutions of  $K_2HPO_4$ ,  $Na_2HPO_4$ ,  $K_2SO_4$ ,  $(NH_4)_2SO_4$ ,  $NaNO_3$ ,  $NaCl$  and  $Na_2CO_3$  of 1N, 0.2N and 0.1N concentrations with a sandy soil in glass tubes 45 cm. in height, found that all salts decreased the capillary

rise of water, as compared with the distilled water. The depressive action of each salt increased with the concentration of the solution. The order in which water reached the top of the tubes for various soluble salts was as follows:  $\text{H}_2\text{O} > \text{NaNO}_3 > \text{NaCl} > \text{Na}_2\text{CO}_3 > \text{K}_2\text{SO}_4 > (\text{NH}_4)_2\text{SO}_4 > \text{K}_2\text{HPO}_4 > \text{Na}_2\text{HPO}_4$ . For two insoluble salts the order was as follows:  $\text{CaSO}_4 > \text{CaCO}_3 > \text{H}_2\text{O}$ . Thus it is shown that phosphates, being the ones that would be absorbed by soil most readily, caused the greatest retardation, while chloride and nitrate of sodium (the least absorbed) had the least influence. The insoluble salts, such as gypsum and calcium carbonate, hastened the capillary rise, as compared with the distilled water. These results are contradictory to the findings of Wollny.

King (11), working with an 0.08 per cent solution of potassium nitrate, found that tubes filled with moist soil when treated with the salt solution lost 22.8 per cent more water than the untreated soil. Since the water was supplied from below in 18-inch tubes, the data show that the application of salt caused both increased capillary rise and evaporation. As a result of later studies by both King himself and others, he takes the opposite view and gives (12) a theoretical reasoning for the retarding action of soluble salts upon capillary movement and evaporation of soil water.

Briggs and Lapham (3) studied the effect of three sodium salts,  $\text{NaCl}$ ,  $\text{Na}_2\text{CO}_3$  and  $\text{Na}_2\text{SO}_4$ , on the capillary rise of water in Sea Island (fine sandy loam) soil, using in parallel 0.5*N* and saturated solutions of these salts. The results show that in the case of 0.5*N* solutions sodium chloride and sodium sulfate caused very little depression in the capillary rise, while sodium carbonate slightly accelerated it. When the saturated solutions were used the first two salts caused very considerable retardation in capillary movement, while sodium carbonate was effective to a lesser degree, though causing a depression. These authors explained the action of sodium chloride and that of sodium sulfate by "the resistance to a tangential shearing stress presented by the thin layer of liquid near its bounding edge" (3, p. 7) when that liquid contains a considerable amount of salt. The action of sodium carbonate was explained by the fact that this salt, being a product of strong base and weak acid, slightly hydrolyzes in water solution. Sodium hydroxide, thus formed, acts on the oily substances of soil producing the water-soluble sodium salt or soap. This cleans the surface of the soil particles, causing its easier and quicker wetting by the rising water. In conclusion the authors make an interesting deduction that "all salts which undergo an alkaline hydrolysis, viz., potassium and sodium carbonates, borates, phosphates, etc.," should affect the capillary power of soils in a similar way, as noticed in the case of sodium carbonate.

Kossovich (13) in 1910, studying sodium chloride and sodium carbonate in decinormal solutions on sand, loess clay and moor clay, found that in this concentration the influence of salts was not marked on the sand but more pronounced on the clays. In general, sodium chloride was found to hasten the rise of water, while sodium carbonate hindered the process.

In view of the conflicting results, as observed by different investigators mentioned above, it was deemed advisable to test several of the substances used in the evaporation experiments as to their action on some agricultural soils. It was decided to use NaCl as one of the least absorbed salts,  $K_2HPO_4$  for the most absorbed salt,  $(NH_4)_2SO_4$  for the intermediate, and CaO for the least soluble substance used. Soils used were Brown silt loam, typical prairie soil, and Drab clay, as the heavy type of soil. With  $(NH_4)_2SO_4$  Elkton clay loam, the same soil as was used in the evaporation experiments, was employed.

[illegible]

in diameter, were filled and uniformly packed with the treated and untreated soil. A double thickness of cheese-cloth was tied around the lower end of each tube. The soil tubes were set in a trough, in which there was a constant circulation of tap water. The height to which water rose in the tubes of different treatments, as observed periodically, is reported in tables 11 and 12. In the test with Elkton clay loam 2 per cent of ammonium sulfate was used. The procedure in this case was practically the same with the exception that the inside diameter of the tubes was 1 inch and that distilled water was employed instead of tap water. The results are recorded in table 13.

TABLE 12

*Effect of different chemical substances on the capillary rise of water in drab clay*

Data represent height of rise of water in inches

DAYS	UNTREATED			NaCl			(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>			K <sub>2</sub> HPO <sub>4</sub>			CaO		
	1	2	Average	1	2	Average	1	2	Average	1	2	Average	1	2	Average
	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.
1	2.3	2.1	2.2	0.8	0.8	0.8	2.0	2.1	2.1	2.5	3.1	2.8	6.0	5.2	5.6
2	3.2	3.1	3.2	1.3	1.2	2.3	3.1	3.2	3.2	3.3	4.1	3.7	7.6	6.7	7.2
3	3.9	3.7	3.8	1.6	1.6	1.6	3.6	3.8	3.7	4.0	4.7	4.4	8.3	7.5	7.9
4	4.3	4.1	4.2	2.0	1.9	2.0	4.1	4.3	4.2	4.3	5.1	4.7	8.7	7.9	8.3
6	5.0	4.8	4.9	2.4	2.5	2.5	4.8	5.0	4.9	4.9	5.7	5.3	9.3	8.6	9.0
8	5.4	5.1	5.3	2.8	2.8	2.8	5.4	5.5	5.5	5.3	6.0	5.7	9.6	8.9	9.3
10	5.8	5.5	5.7	3.2	3.1	3.2	5.8	5.9	5.9	5.5	6.2	5.9	9.8	9.1	9.5
12	6.3	5.9	6.1	3.5	3.5	3.5	6.2	6.4	6.3	6.0	6.8	6.4	9.8	9.3	9.6
14	6.6	6.2	6.4	3.7	3.7	3.7	6.5	6.8	6.7	6.3	7.1	6.7	10.0	9.4	9.7
16	7.0	6.5	6.8	4.0	3.9	4.0	6.9	7.1	7.0	6.6	7.3	7.0	10.0	9.4	9.7
18	7.3	6.8	7.1	4.3	4.3	4.3	7.2	7.3	7.3	7.0	7.7	7.4	10.1	9.5	9.8
21	7.7	7.2	7.5	4.7	4.6	4.7	7.7	7.8	7.8	7.3	8.0	7.7	10.2	9.6	9.9

### Results and discussion

It is interesting to note that in the brown silt loam (table 11) sodium chloride caused a very marked depression in the capillary rise of water, and potassium phosphate slightly accelerated it, while neither ammonium sulfate nor calcium oxide had any pronounced influence. The action of sodium chloride and ammonium sulfate in drab clay (table 12) was very similar to their action on brown silt loam, namely, the first one retarded the capillary movement of water, while the second one had no influence on it. Potassium phosphate, unlike in its action on brown silt loam, had no effect on the rate of capillary flow of water. Calcium oxide, on the other hand, considerably accelerated the rise of capillary water, the capillary action being mostly in the first two or three days, almost stopping toward the end of the experiment.

In the light of the present knowledge of absorption of salts by soils the results with sodium chloride were not unexpected. This salt, being but

little absorbed, would greatly increase the viscosity of the soil solution, thus causing a retardation in the movement of capillary water. This general rule, however, evidently does not hold true in the case of ammonium sulfate, which, according to the determination of the osmotic pressure of the soil solution of the treated soil (tables 7, 8, 9 and 10), greatly increased the concentration of soil solution in every soil studied. We may very conveniently apply Briggs and Lapham's (3) explanation for the action of potassium phosphate, which is based on the assumption that potassium phosphate hydrolyzes in the soil, forming potassium hydroxide. The latter base acts on the oily substances in the soil, dissolves them, forms soap, and thus assists in the wetting of the soil by the soil solution. The same explanation, however, can not be applied to the action of ammonium sulfate.

TABLE 13

*Effect of ammonium sulfate (2 per cent) on the capillary rise of water in Elkton clay loam*

Data represent height of water rise in inches

DAYS	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>			UNTREATED		
	1	2	Average	1	2	Average
	in.	in.	in.	in.	in.	in.
1	8.5	7.5	8.0	10.0	10.8	10.4
2	10.5	9.0	9.8	12.8	13.3	13.1
3	11.5	10.3	10.4	14.0	14.8	14.4
4	12.7	11.0	11.9	15.8	16.3	16.1
6	14.3	12.5	13.4	18.0	18.3	18.2
8	15.3	13.8	14.6	19.5	19.8	19.7
10	16.3	14.8	15.6	20.8	21.3	21.1
12	17.5	15.8	16.7	22.8	22.8	22.8
14	18.0	16.3	17.7	24.0	24.0	24.0
19	19.0	17.5	18.3	25.5	25.5	25.5
26	20.5	19.0	19.8	28.3	28.3	28.3
30	21.3	19.8	20.6	29.3	29.3	29.3

The action of calcium oxide on the physical properties of drab clay was evidently responsible for the acceleration of water movement. The behavior of the water curve in the lime tubes was very similar to that which could be expected in sandy soil. It is possible that the coagulating action of lime on the colloids of the drab clay produced a granular structure which resulted in a reduction of the internal surface similar to that found in sandy types of soil. Being a lighter type, brown silt loam was not sufficiently modified by lime in this respect to cause the change in its property of capillarity.

Referring now to table 13, one notices that in this case the application of 2 per cent ammonium sulfate to Elkton clay loam caused a very pronounced decrease in the capillary rise of water, as compared with the untreated soil.

CORRELATION BETWEEN ACTION OF DIFFERENT SALTS IN EVAPORATION  
AND CAPILLARY RISE OF WATER

In studying tables 1, 2, 3, 4, 5, 11, 12 and 13, one notices but very little correlation between evaporation from soils under different treatments and the capillary rise of water in some soils. It is true that sodium chloride, one of the most efficient in depressing the evaporation of water, causes a considerable decrease in the capillary rise of water. This case, however, is rather an exception and not a rule. Neither ammonium sulfate, potassium phosphate, nor calcium oxide show any such correlation between these two phenomena. Ammonium sulfate caused considerable decrease in the evaporation of water, but was without influence on the capillary rise, when applied at the rate of 1 per cent, and displayed its action only when applied at the rate of 2 per cent. The lack of correlation in the case of potassium phosphate and calcium oxide is still more pronounced. The first substance in the case of brown silt loam and the second one in the case of drab clay caused an acceleration of capillary rise of water, yet both these substances caused a decrease in the evaporation of water in the respective types of soil. In this respect the action of lime is most interesting. It caused the greatest decrease in the amount of evaporated water in clay soil in spite of the fact that in the similar soil it increased the capillary rise of water (tables 4 and 12).

EFFECT OF DIFFERENT CHEMICAL SUBSTANCES ON THE MOISTURE CONTENT  
OF BROWN SILT LOAM

In view of the fact that the evaporation of water from several soils treated with various chemical substances has little dependence upon the effect of these substances on the capillary water rise, it would be interesting and instructive to know whether or not a given soil, so treated, would contain more water than the untreated soil, and how this water is distributed at different depths of the soil column. King (10), for instance, has observed that, while manured and unmanured plots had practically the same amount of water in 6 feet of soil, the manured plot had considerably more water in the first and second foot than the unmanured plot. Although the solid portion of manure may have played the largest part in modifying the physical property of the soil, yet the rôle of the soluble salts in manure also might be appreciable.

In order to throw some light on this question it was decided to add some chemical substances to brown silt loam, as one of the most typical soils of the prairie region. The substances selected were: sodium chloride, as one of the least absorbed salts; potassium diphosphate, as one of the most absorbed salts; and calcium oxide, the substance often used for correcting soil acidity. Besides, its conversion (partial at least) into a carbonate form, which is most commonly used in farm practice, would take place in the soil under the conditions of this experiment.

*Procedure*

Galvanized iron cylinders, 18 inches long and 6 inches in diameter, were used for the purpose. They were regular evaporimeters of a large type. Around the lower end of each cylinder a double thickness of cheese-cloth was tied securely. The air-dried brown silt loam, sifted through a 1/16-inch sieve, was packed uniformly into the cylinders. Then the soil of the

TABLE 14

*Effect of applications of chemical substances on the moisture content of brown silt loam at different depths in cylinders, water being supplied from below*

DEPTH OF CYLINDER FROM SURFACE	DUPLI- CATE	UNTREATED			NaCl			K <sub>2</sub> HPO <sub>4</sub>			CaO		
		Cylin- der 1	Cylin- der 2	Aver- age of four	Cylin- der 1	Cylin- der 2	Aver- age of four	Cylin- der 1	Cylin- der 2	Aver- age of four	Cylin- der 1	Cylin- der 2	Aver- age of four
in.		per cent	per cent	per cent	per cent	per cent	per cent	per cent	per cent	per cent	per cent	per cent	per cent
1	1	35.33	35.53		36.05	34.79		37.48	38.79		38.95	39.60	
	2	35.40	36.55	35.70	35.70	34.96	35.38	37.40	38.60	38.07	38.69	39.52	39.19
2	1	36.85	37.37		40.62	39.93		39.83	40.17		41.36	41.97	
	2	36.70	37.71	37.16	40.31	39.68	40.14	39.68	39.91	39.90	40.63	42.07	41.51
3	1	37.48	39.35		39.95	39.41		39.62	40.16		41.32	41.79	
	2	37.61	37.80	38.06	40.03	39.67	39.77	39.79	40.42	40.00	40.84	41.14	41.27
4	1	38.07	39.15		39.53	39.67		38.60	38.86		38.66	38.57	
	2	37.66	37.99	38.22	39.41	39.83	39.61	38.49	38.92	38.72	38.71	39.26	38.80
5-6	1	38.69	39.65		40.06	39.64		39.36	39.42		39.29	39.03	
	2	38.68	39.37	39.10	40.00	39.26	39.74	39.11	39.60	39.35	39.12	39.25	39.17
7-8	1	40.36	41.04		39.54	38.77		38.56	38.11		39.12	39.44	
	2	40.50	41.20	40.78	39.52	38.34	39.04	38.28	38.33	38.32	39.24	39.78	39.40
9-10	1	40.50	40.50		37.51	37.29		35.67	35.91		36.63	37.33	
	2	40.78	40.37	40.46	37.68	37.32	37.45	36.20	36.23	36.00	36.61	36.75	36.83
11-14	1	40.11	39.99		39.27	38.16		37.24	37.45		36.99	37.48	
	2	39.99	40.12	40.05	38.82	37.86	38.65	37.36	37.53	37.40	36.97	38.25	37.42
15-18	1	39.04	38.79		40.05	38.66		37.58	37.52		37.60	37.79	
	2	39.25	39.39	39.41	40.28	38.45	39.36	37.51	37.51	37.53	37.75	37.99	37.78

3 surface inches was removed and thoroughly mixed with 19.83 gm. of sodium chloride, potassium phosphate or calcium oxide. This represents an application of one ton of the substance per acre, as the surface of the soil exposed to evaporation equals to 28.27 square inches. The soil with the applied salt was packed again into the cylinder. The cylinders were set into a proper receptacle with water, and allowed to stand in a greenhouse for 33 days.

Then different layers of soil were taken out and the moisture content was determined. The results are given in table 14 and presented graphically in figure 3. During 10 days (January 13 to 23) the amount of evaporated water from each cylinder also was determined, and the results are given in table 6.

### *Results and discussion*

The results showing the effect of different substances were discussed in a general way with other evaporation data in the first part of this article. It might be mentioned in this connection that the results for the evaporation of the brown silt loam agree very closely with the results for the other soils studied. Studying the data in table 14 and the accompanying figure 3, one observes

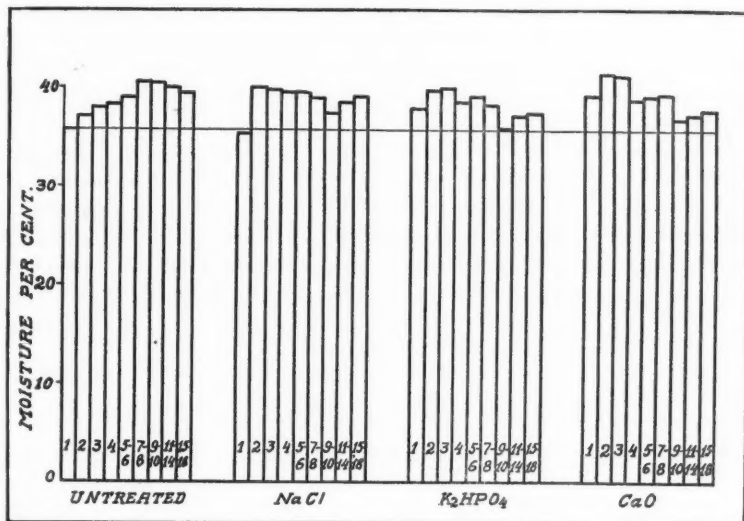


FIG. 3. MOISTURE CONTENT OF BROWN SILT LOAM AT DIFFERENT DEPTHS IN CYLINDERS AS INFLUENCED BY VARIOUS TREATMENTS

The treatment was in the first 3 inches of soil. The numbers in the columns represent the depth in inches from the surface.

several features that might be of some importance. In the untreated soil the per cent of moisture gradually increased with the depth down to the 7-8 inch layer. Then it remained practically constant, or even slightly decreased. In the cylinders treated with sodium chloride the surface inch had practically the same amount of water as the surface inch in the untreated cylinders; the moisture, however, suddenly increased in the second inch to the highest per cent in the cylinder and remained so down to the 9-10 inch layer.

A somewhat similar condition was observed in the  $K_2HPO_4$  and CaO cylinders in that the second- and third-inch layers had the highest moisture content. There were, on the other hand, some considerable differences, since in the cylinders with the latter two treatments the moisture content of the 4-8 inch depth, being practically uniform, ran somewhat lower than the moisture content at the 2-3 inch depths of the same cylinders. In all six treated cylinders there was a noticeable sudden lowering in the moisture content at the depth of 9-10 inches. This may or may not be significant.

There is still another interesting difference between soils treated with potassium monophosphate and calcium oxide, as compared with the untreated soil. The moisture content of the first inch in the treated soils was very markedly higher than that of the surface inch in the untreated soil. Again, taking the treated brown silt loam as a whole, under the conditions of this experiment, one notices that the amount of moisture in the first 8 inches from the surface is considerably greater than in the untreated soil to the same depth. In spite of this fact, however, the evaporation from the surface of the treated soil was less than in the untreated soil. The water was brought up from below and remained right beneath the surface.

It might be mentioned in this connection that in the alkali or niter spots there is found an abundance of moisture in soil right beneath its surface. The observations of Headden (9) might be of some interest to those wishing to study this problem. It is very probable, therefore, that the salts accumulated at the surface are largely responsible for the abundance of water held beneath the very thin layer of soil in alkali regions, though the warm air and high winds of the West may contribute somewhat to creating these conditions, as has been suggested by Buckingham (4).

#### EFFECT OF ACCUMULATED SALTS ON RATE OF WATER EVAPORATION

During the progress of the experiment it was observed that on the surface of some treated soils there would occur an accumulation of salts which were brought up with the water and deposited in the form of a crust. In the case of some salts this crust was heavier than in others. Ammonium sulfate, for instance, formed a very heavy crust, while this was practically not noticeable in the case of sodium chloride. The question might be raised whether the crust so formed would influence the rate of water evaporation. If it exerts some action, it should be noticeable in the differences in the amount of evaporated water from the treated and the untreated soils. For this reason tables 15 and 16 and figure 4 are given. They show the progress of water evaporation in several-day periods of Sassafras medium sandy loam and Elkton clay loam.

Judging from the figures in these tables and the diagram, there was no pronounced difference between the rate of evaporation at the end of the experiment and that at the beginning. The differences in water evapora-

tion from treated and untreated soils began at once and progressed gradually and rather uniformly to the end. The curve of the heavy-crust-forming ammonium sulfate did not differ in its tendency from that of the non-crust-forming sodium chloride.

TABLE 15

*Effect of different chemical substances on the evaporation of water from Sassafras medium sandy loam*

Data represent grams of water evaporated from soil cylinders at different periods; average of two determinations taken

TREATMENT	DAYS									
	4	8	13	17	22	27	32	36	40	48
	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.
Untreated.....	52	99	149	193	245	298	358	424	490	626
(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub> .....	35	71	105	137	176	215	269	327	380	480
NaCl.....	27	55	85	113	141	174	223	270	312	393
KH <sub>2</sub> PO <sub>4</sub> .....	43	85	128	167	210	254	316	383	450	580
CaO.....	49	93	141	183	229	275	333	399	466	604

TABLE 16

*Effect of different chemical substances on evaporation of water from Elkton clay loam*

Data represent grams of water evaporated from soil cylinders at different periods; average of two determinations taken

TREATMENT	DAYS						
	5	10	15	21	25	30	35
	gm.	gm.	gm.	gm.	gm.	gm.	gm.
Untreated.....	129	231	382	542	648	819	900
(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub> .....	85	149	239	344	415	432	590
NaCl.....	58	102	168	237	279	353	384
KH <sub>2</sub> PO <sub>4</sub> .....	95	167	261	356	415	511	557
CaO.....	36	66	110	171	204	272	313

#### EFFECT OF TEXTURE OF SOIL ON THE RATE OF EVAPORATION OF WATER

As recorded in the description of the procedure in conducting the experiments on the effect of chemical substances on the evaporation of soil water, a Livingston's (15) atmometer cup was used with the evaporimeters. This atmometer being the same throughout the experiment, it afforded an opportunity to study the effect of the texture of the soil on the rate of water evaporation, when water was supplied 12 inches below the surface. Table 17 gives the amount of water evaporated from the untreated cylinder and from the atmometer for each soil studied, and also the ratio of the first to the latter.

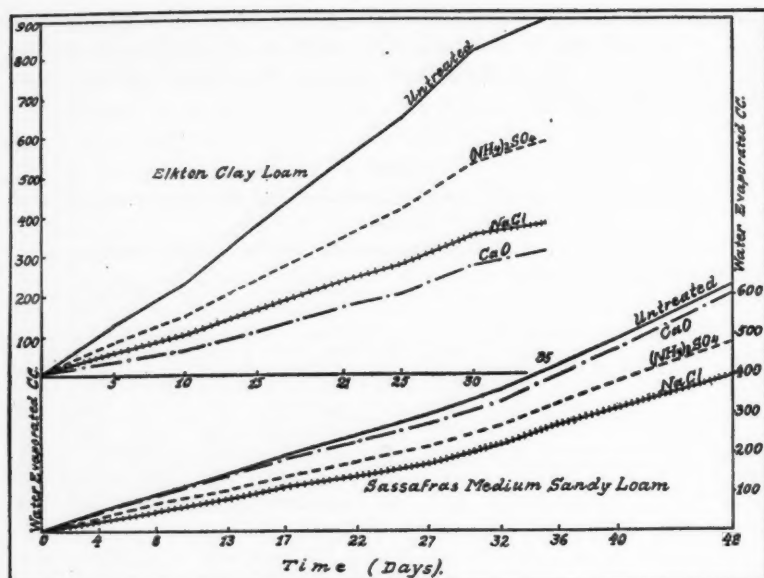


FIG. 4. PROGRESS OF EVAPORATION OF WATER FROM ELKTON CLAY LOAM AND SASSAFRAS MEDIUM SANDY LOAM AS INFLUENCED BY VARIOUS TREATMENTS

Note the position of the CaO curve in respect to those of the two salts in the different types of soil.

TABLE 17

Influence of texture of the soil on the evaporation of water from soil cylinders 12 inches in depth, water being supplied from below

SOIL	WATER EVAPORATED FROM UNTREATED CYLINDER (A)	WATER EVAPORATED FROM ATMOMETER (B)	RATIO A:B
	gm.	gm.	
Sea sand.....	334	656	0.509
Sassafras medium sandy loam.....	626	708	0.884
Penn loam.....	960	697	1.377
Elkton clay loam.....	900	590	1.525
Muck.....	957	567	1.688

This ratio was the smallest for the sea sand, and gradually increased with the increase in the fineness of the soil. Thus, for mineral soils the ratio was greatest in the case of Elkton clay loam. In other words, when water was supplied at 12 inches below the surface of the soil, the clay soil evaporated water most rapidly, and the sand most slowly. Muck, being composed largely of organic material, evaporated water even more rapidly than the Elkton clay loam.

## PRACTICAL DEDUCTIONS

Besides the theoretical considerations involved in the interpretation of these results, there might be mentioned an important practical deduction that could be made with considerable safety. Although it is always desirable and highly advisable to check all laboratory and greenhouse pot and cylinder experiments by the more elaborate field experiments, the former often serve as an indicator (though qualitative) as to what would happen in the field under similar treatment. These deductions are still more trustworthy if the greenhouse experimental results correlate with the practical field observations. For this reason the results presented above have considerable practical significance.

Several soluble salts or lime, when applied to some typical agricultural soils, do exert a very pronounced influence on the rate of water evaporation and also on the amount of water present at or near the surface of the soil. From practical field observation, in alkali regions, we do not know whether or not the salts decrease the evaporation of water, but we do know that under those conditions an abundance of water is held at the surface. Since the studied soluble salts are not able to hasten the capillary rise of water in soils to an appreciable extent (sodium chloride diminished it considerably), it is reasonable to conclude that even the field observations bear out the point that soluble salts in soil do decrease the evaporation of water. This will help us to understand why alkali soils are so wet directly beneath the surface.

Though these experiments were carried on in the greenhouse, it is safe to suppose that an application of commercial fertilizers to soils under field conditions would tend to help in the conservation of soil moisture through a diminished evaporation. Besides, it would help to bring the water to the surface and thus make it more available for the growing crop. This would be especially valuable at the time of the germination of seed, for which a right amount of moisture, besides the right temperature, might be the most important factor.

With barley, for instance, it was found by the author (19) that with several agricultural soils there must be present a considerable amount of water before the germination would take place. This being the case, it would seem that a fair amount of soluble salts at the surface of soil would help to make the conditions more favorable for seed germination and an early growth. This contention is well corroborated by a fairly common practice in some sections of the country to apply some readily available fertilizer at the time of seeding.

It is true that the application of salts in these experiments were too excessive to be practiced in actual farm operations. It stands to reason, however, that some action of various salts would be felt when applied in smaller amounts. The experiment performed with various amounts of ammonium sulfate on Penn loam in the same cylinders, as described in the first part of the article, strengthens this contention. The results are presented in table 18

and show that even the smallest application exerted a pronounced influence on the evaporation of soil moisture. This application, 250 pounds per acre, lies within the range of actual farm practice.

So far as the results with lime are concerned, they represent an amount frequently applied to soils to correct the soil reaction. Indeed, much higher

TABLE 18  
*Effect of different amounts of ammonium sulfate on evaporation of water from Penn loam*  
Duration 33 days

TREATMENT	CYLINDER		AVERAGE	DECREASE OVER UNTREATED	WATER SAVED BY TREATMENT
	1	2			
	gm.	gm.	gm.	gm.	per cent
Untreated .....	700	740	720		
250 lbs. $(\text{NH}_4)_2\text{SO}_4$ .....	660	668	664	56	7.8
500 lbs. $(\text{NH}_4)_2\text{SO}_4$ .....	625	634	635	85	11.8
1000 lbs. $(\text{NH}_4)_2\text{SO}_4$ .....	598	624	611	109	15.1
2000 lbs. $(\text{NH}_4)_2\text{SO}_4$ .....	560	570	565	155	21.5

applications of lime sometimes are recommended and made. Thus, it would seem that the effect of lime on evaporation and on the distribution of water in some agricultural soils might be very considerable. This would be especially true in heavier types of soil and, indeed, it is on this type of soil that lime is most advantageous, as observed in farm practice.

#### SUMMARY

The experimental work recorded in this paper was performed with ammonium sulfate, potassium sulfate, magnesium sulfate, sodium chloride, calcium nitrate, potassium phosphate and calcium oxide, with which some agricultural soils were treated in order to ascertain the influence these salts and the base would have on the evaporation, capillary rise and eventual distribution of water in soil.

The indications are that the following conclusions might be drawn from the results obtained:

1. Soluble salts materially decrease the evaporation of soil moisture.
2. There is a direct dependence of the efficiency of salts in decreasing the water evaporation upon the osmotic concentration of the soil solution in the surface inch of soil. With few exceptions the results tend to show that the greater the osmotic concentration of soil solution in the first inch of soil the greater is the depression of the evaporation of moisture.
3. For the soluble salts studied sodium chloride and calcium nitrate were most effective in checking the evaporation of water, and potassium sulfate and potassium phosphate were least effective, while ammonium sulfate and magnesium sulfate occupied an intermediate position.

4. Calcium oxide in this respect was least effective in sea sand and sandy loam and most effective in clay loam, as compared with the soluble salts studied.

5. With two agricultural soils sodium chloride decreases the capillary rise of water. Calcium oxide in drab clay and potassium phosphate in brown silt loam show a tendency to accelerate the water rise. Ammonium sulfate shows no pronounced effect, when applied in the same amount.

6. Sodium chloride, potassium phosphate and calcium oxide very materially influence the distribution of moisture in brown silt loam. There is a very pronounced tendency for treated soil to contain more water in the first 8 inches, as compared with the untreated soil.

7. Soil treated with potassium phosphate or calcium oxide even in the surface inch contained more water than the untreated soil, and yet evaporation from treated soil was decreased.

8. Comparing the untreated soils, when water was supplied at 12 inches below the surface, the extent of evaporation depended on the texture of the soil. With the increase in the amount of fine material in the soil the evaporation increased.

The work recorded in this article was partly done at the New Jersey Agricultural Experiment Station while the author was a graduate student at Rutgers College. To Dr. J. G. Lipman, under whose supervision the work was started, the author is indebted for his interest in the work and for many helpful suggestions. The work was finished at the Illinois Agricultural Experiment Station, and author is very grateful to Prof. J. G. Mosier and Dr. R. S. Smith for the use of the laboratory equipment, and to Dr. R. Stewart for critically reading the manuscript.

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## THE EFFECT OF GYPSUM ON BACTERIAL ACTIVITIES IN SOILS<sup>1</sup>

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### INTRODUCTION

The discovery of gypsum and its fertilizing value was made at about the same time in Germany and in France in the latter part of the eighteenth century. The use of gypsum spread quickly to other countries, first to America and considerably later to Great Britain. Just how it acts is little understood, but the two explanations which have been given are that it supplies the sulfur needed for plant growth, or that it acts as a corrective agent by favoring beneficial groups of bacteria, while the development of injurious species is prevented. Recently, some authors have secured results which indicate that sulfates act on complex compounds like the silicates liberating potassium and phosphorus. In other words, there are indications that sulfates may render the essential plant-food constituents available for the use of plants.

The need of sulfur as a plant-food is evident from the fact that the proteins of plants contain sulfur, and there is no question but that plants utilize sulfur in the form of sulfates just as they utilize phosphorus as phosphates and and nitrogen as nitrates.

Sulfur has been supposed to be present in soils in sufficient amounts to keep all crops supplied. Recently, however, the possibility of value from using sulfur as a fertilizer has been indicated.

Many comparatively recent analyses made at Rothamsted and elsewhere have shown that certain soils are deficient in sulfur and that there is a rather constant ratio between phosphorous and sulfur. Soils that are low in phosphorus and need phosphorus fertilizers may therefore respond also to sulfur fertilizers. The application of phosphorus in the form of acid phosphate supplies sulfur as calcium sulfate along with phosphorus and when this material is used it may be possible to insure an ample supply of sulfur to meet the requirements of crops.

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<sup>2</sup> Opportunity is taken to thank Dr. P. E. Brown, Chief in Soil Chemistry and Bacteriology, for his valuable suggestions and criticisms throughout this work and for reading the manuscript.

There are certain soils, especially in the Middle West, which are fairly well supplied with sulfur and probably would not respond to sulfur fertilization at the present time. But the fact that the content of sulfur is gradually being exhausted in some soils should not be lost sight of. Experiments at Rothamsted showed that the average annual loss of sulfur by drainage amounted to 50 pounds per acre and the amount of sulfur trioxide precipitated with the rain was found to be about 15 to 20 pounds per acre per annum. The conclusions reached were, therefore, that the losses of sulfur from the soil by drainage and cropping are much larger than can be met by the amounts brought down by rain and that some carrier of sulfur such as farm manure, acid phosphate, ammonium sulfate, sulfate of potassium, or gypsum must be applied to soils, if they are to be maintained in a permanently fertile condition. Of late, the use of gypsum as a fertilizer has been tested by a few of the agricultural experiment stations in the United States and it is being recommended in some sections of the country as a profitable fertilizing material. Extensive experiments should be carried out in the field, however, before the use is recommended under any particular conditions. Tests are now under way in Iowa to determine its value and in other states there is a considerable interest manifested in gypsum. It may be that the material will play an important rôle in many states in maintaining fertility.

#### HISTORICAL

Before entering upon the discussion of the experimental data obtained in this work, a brief history of the results secured by previous investigators may be given. Comparatively few studies have been made of the effects of gypsum on bacterial activities but some tests of its influence on ammonification, nitrification and azofication have been carried out with interesting results.

##### *The effect of gypsum on bacterial activities*

Severin (44) in laboratory tests with sterilized and unsterilized manure (inoculating in the latter case with pure cultures of organisms capable of inducing ammoniacal fermentation as well as with water extracts of manure), found that the addition of 4 per cent gypsum to the manure intensified the decomposition of the manure 10 to 20 per cent and at the same time prevented any loss of ammoniacal nitrogen.

Heinrich (19) found, likewise, that gypsum was a very effective preservative of manure. C. B. Lipman (22) concluded from his work that gypsum stimulated the beneficial soil organisms on the roots of leguminous plants.

J. G. Lipman (25) tested the influence of gypsum on the number of soil bacteria and concluded that applications of gypsum were not injurious to soil bacteria, nor to the plants themselves. In fact he observed from the data secured that the amounts of nitrate nitrogen expressed as parts per million were favorably affected by the addition of gypsum. Lipman and his

associates (28) found that the addition of gypsum to a soil often increased the total nitrogen of the crop removed from the soil. The same authors (27) experimenting on the availability of nitrogenous materials as measured by ammonification, demonstrated that the so-called stimulants—potassium iodide, and copper, zinc, manganese, ferrous and calcium sulfates—gave varying and inconclusive results, while phosphates appeared to favor ammonification. Lipman found from box experiments that the nitrogen content of soybeans was distinctly increased by the use of lime, while gypsum appeared to have no effect. Neither lime nor gypsum showed any appreciable effect on buckwheat.

Dezani (10) in his experiments showed that no material increase in nitrification was obtained when gypsum was added in amounts varying from 0.5 to 2 per cent. Lemmerman and Fresenius (21) found that the addition of calcium carbonate to soils in pots to the extent of 1 per cent reduced the volatilization of ammonium carbonate and increased the absorptive power of the soil for ammonia. Caustic lime had the opposite effect. Calcium sulfate and calcium chloride reduced the loss solely by their direct action on the ammonium carbonate. Patterson and Scott (38) studied the influence of caustic lime, calcium carbonate, gypsum, ferric hydrate, sodium chloride, citric acid, starch, sugar and acid phosphate on nitrification in soils and found that caustic lime practically stopped all nitrification. Calcium carbonate was the most efficient of the substances tested in stimulating the process and gypsum had little effect on nitrification. Nishimura (2) reported that gypsum and Kainit were found to be less effective than acid phosphate in fixing ammonia.

Fred and Hart (15), found that the sulfates of calcium and potassium increased ammonification to a small extent and calcium sulfate gave a slight increase in carbon-dioxide production. They further claimed that sulfates, although as low in amount in most soils as phosphates, would not in all probability have the same effect on the crop-producing power of soils as phosphates, and they attribute the inequality to the differences in the effect of the two acid radicals on the soil.

Peck (39) studied ammonification, nitrification, denitrification and azofication with three samples of soils by inoculating nutrient solutions with small amounts of the soil, or by observing the progress of nitrogen transformation in the soils themselves. He found that the addition of lime as carbonate, sulfate or phosphate stimulated ammonification; as regards nitrification calcium carbonate exerted the most favorable action, while gypsum had no effect. Sugar showed an increased azofication. Hart and Tottingham (18) in their work showed that sulfates as compared with soluble phosphates had very little effect on the soil flora.

Pitz (41) in his work with sulfur and calcium sulfate concluded that the addition of calcium sulfate to the soil had no marked effect on the total number of bacteria growing on ordinary agar plates, nor did it produce any marked

increase in ammonification or nitrification. The material was found, however, to stimulate the growth of pure cultures of red clover bacteria and also to increase the root development of red clover in nutrient solution and in soil extract. In small amounts it was also found to increase the yield of red clover and the number of nodules.

Brown and Johnson (7) found that calcium sulfate in ordinary applications had no detrimental effect on sulfonation, but very large applications might decrease the rate of oxidation of sulfur.

*The effect of gypsum on crops*

The effect of gypsum on crops has been studied to some extent and the influence on legumes noted especially. Hart and Peterson (17) determined the sulfur content of a number of common farm crops and in agreement with other investigators they showed that the quantity is much higher than that found by Wolff in the ash from such products. Withycombe (50) reported the yields of green clover from plots receiving different quantities of gypsum and showed a gain of 22 per cent in favor of gypsum. Dymond and his associates (13) from their investigations conclude as follows:

There is not sufficient sulfuric acid in the soil or supplied by rain for heavy-yielding crops rich in albuminoid, either for the production of the greatest yield or the highest feeding value, and for such crops a sulfate should be included in the artificial manure. For cereal crops and for permanent pastures, the soil and the rain provide all the sulfuric acid necessary.

Takeuchi (49) carried on pot experiments with peas, beans, oats, rice and spinach in which gypsum was used in connection with ammonium sulfate, sodium nitrate, potassium sulfate and different forms of phosphorus. He observed that as a rule gypsum decreased the yield when used in connection with acidic fertilizers and increased the yield when used with basic fertilizers. He found further, that gypsum exerted a favorable influence in overcoming the injurious effects of magnesium.

Dusserre (12) found that the application of gypsum greatly increased the yields of potatoes and beets and in the case of potatoes, the mineral matter and starch were also considerably increased by the use of gypsum. Aston (3) reported that gypsum was the most effective lime compound in increasing the yield of cruciferous plants on soils containing an excess of magnesia, but ground limestone was the most effective in increasing the yields of oats and grasses. Meyer (31) found that calcium and magnesium carbonates had a beneficial effect on the yield of red clover, mustard and potatoes on acid soils, whereas gypsum reduced the yield. Rusche (42) demonstrated that magnesium and calcium sulfate generally had a good effect on the germination of barley, beans, beets, alsike clover, red clover, white clover, wheat and other seeds.

Patterson (37) found that the application of raw-rock phosphate gave better results than gypsum in a rotation of corn, wheat, timothy and clover

on a sandy soil. Shedd (45) showed that the addition of sulfur or gypsum to a fertilizer containing only nitrogen, potassium and phosphorus, when applied to a Graves County soil, gave a decided increase in growth of Yellow Pryor tobacco over the fertilizer alone. G. O. Brown (6) in his experiment with calcium sulfate found that an application of air-slaked lime, followed by a 100-pound application of land plaster after the first cutting of alfalfa, resulted in a greatly increased vigor and a total yield considerably in excess of the untreated crop.

The most recent investigation along this line was reported by Miller (32) who worked with three Oregon soils. The first was taken mainly for its high sulfur content, the second one because it did not respond to sulfur treatment in the field, while the third did respond to elementary sulfur fertilizer. The highest sulfur content was 0.183 per cent and the lowest 0.02 per cent. The results show that the addition of calcium sulfate and elementary sulfur enhanced the growth of rape, oats and clover grown in pots in the greenhouse. The great increase in the nitrogen content of the clover grown on the soil where sulfates had been added was the result in all probability of the stimulating action of the sulfate on the legume bacteria. The sulfate increased the root development and the number of nodules on the clover grown in the soil in pots. Tacke (48) explained in his work that the injurious effect of gypsum observed especially in the case of leguminous plants was due to the setting free of acids to which such plants are especially sensitive.

Parshad (36) in his work with gypsum, found that it proved a valuable fertilizer on indigo and that top-dressing was the least beneficial method of applying it. Katayama (20) in experiments carried on at Tokyo, showed that rice yielded better and had a better color when grown on land manured with gypsum. C. B. Lipman and Gericke (23) found that calcium sulfate in varying quantities antagonized the sodium sulfate in clay adobe soil where barley was grown.

#### *The effect of gypsum on available plant-food*

Several experiments have indicated an effect of gypsum on the solubility of plant-food.

Storer (46) showed a greater amount of phosphorus in clover taken from land manured with gypsum. Pfeffer (40) states that Knop found that where seeds were grown in water containing calcium sulfate, the calcium of the salt was absorbed in a somewhat greater amount than the acid. If this is true, it is easy to see how calcium sulfate can assist in the assimilation of phosphorus even though the phosphates are found to be less soluble in a calcium sulfate solution.

Dusserre (11) found that the most effective agents in rendering soil potash soluble in distilled water were gypsum and sulfate of ammonia. Dumont (8), studying the effect of gypsum upon both granitic soils and the separates

from these obtained by mechanical analysis, found that when mixed with about one-third its weight of gypsum, moistened and allowed to stand, the soil gave increasing amounts of water-soluble potash with lengthening periods of contact between soil and gypsum.

Schreiber (43) reported experiments which indicated that gypsum had a marked though limited effect in setting free the potash of the soil. Morse and Curry (34) found that lime and gypsum in contact with feldspar increased the solubility of potassium. Soane (47) in his general discussion of a series of pot experiments to determine the chemical effect of the application of gypsum on soils, reported that the effect of gypsum alone was insignificant. When combined with soluble potash, however, it seemed to produce a beneficial effect.

Morse and Curry (35) found that when powdered feldspar was treated with gypsum the solubility of potash in water was increased. Bradley (4) found that gypsum added both to soils from western Oregon and to the mineral pegmatite markedly increased the content of water-soluble potash. Andre (1) observed a greatly increased solubility of the potash of microcline when this was treated with gypsum. C. B. Lipman (24) concluded that calcium sulfate is the most powerful soil stimulant we have and that its effect is due mainly to its liberation of plant-food, especially potassium.

McMillen (30) found that when various soils, mixed with 1 per cent of gypsum, were kept for 3 months under moisture conditions similar to those prevailing in the field there were marked increases in the content of water-soluble potash. It is suggested, that in experiments previously reported by various investigators where gypsum was not found to bring about such an increase the lack of any action might be due to the fact that the condition of contact between the soil and gypsum was not the same as would occur in the field.

Frap (14) found that the addition of sulfate of lime, nitrate of soda, or other salts, has no such effect upon rendering potash available to plants as has been claimed. Briggs and Breazeale (5) reported that gypsum solutions depressed the solubility of the potassium in orthoclase, the quantity of potash in solution decreasing progressively as the concentration of the calcium sulfate increased. McCool (29) found very recently that the effect of the calcium sulfate on the rate of the formation of soluble potash was negligible in the first period of 2 days and slightly reduced it in the second period of 17 days. He claims that soils of different texture and composition probably would be affected somewhat differently.

Greaves and Carter (16) in their recent investigation also reported that the strong stimulant sodium chloride to a great extent acts by rendering phosphorus soluble, whereas the equally strong stimulant calcium sulfate acts by rendering more nitrogen available.

## EXPERIMENTAL

Dumont (9), summarizing in his paper the theories advanced regarding the value of gypsum when applied to the soil, points out that it serves as a stimulant, that it serves as a plant-food, that it acts as an absorbent for volatile compounds like ammonia, and that it helps in making plant-food available.

The work presented in the subsequent pages was planned to throw some light on the following questions:

- (a) Does calcium sulfate favor the activities of desirable organisms of the soil?
- (b) Does it serve as a plant-food?
- (c) Does it make certain plant-food constituents more available?

*Plan of the experiments*

The soil used in these experiments was secured from an orchard at Ames and is classified as Miami silt loam. The chemical analysis is given in table 1.

TABLE 1  
*Soil analysis*

Total sulfur .....	0.168 per cent
Total sulfates .....	0.005 per cent
Total potassium .....	1.410 per cent
Water-soluble potassium .....	0.0027 per cent
Limestone requirement .....	2500 pounds per acre

Forty-eight pots were each filled with 40 pounds of soil which had been sifted through a coarse sieve, so as to remove the roots and pebbles. The treatment of these pots was as follows:

- 1, 2 Check
- 3, 4 Limestone to neutralize acidity plus 2 tons ( $3\frac{1}{2}$  tons)
- 5, 6 100 pounds  $\text{CaSO}_4$  per acre
- 7, 8 500 pounds  $\text{CaSO}_4$  per acre
- 9, 10 1000 pounds  $\text{CaSO}_4$  per acre
- 11, 12 100 pounds  $\text{CaSO}_4$  per acre plus limestone ( $3\frac{1}{2}$  tons)
- 13, 14 500 pounds  $\text{CaSO}_4$  per acre plus limestone ( $3\frac{1}{2}$  tons)
- 15, 16 1000 pounds  $\text{CaSO}_4$  per acre plus limestone ( $3\frac{1}{2}$  tons)

The first set of these pots from 1 to 16 were kept fallow, the second set of 16 pots similarly treated were seeded to wheat, and the third set of 16 pots with similar treatment as the first two sets, were seeded to red clover. The pots were kept in the greenhouse under uniform temperature conditions. The moisture content of the soils in the pots was kept up to 15 per cent of the dry weight of the soil.

After the seeds had germinated in the pots, the plants of red clover and wheat were thinned so as to leave only 6 plants in each pot.

## BACTERIOLOGICAL

In order to ascertain whether gypsum favors the activities of beneficial soil organisms it was planned:

1. To study the action of gypsum on bacterial activities as measured by ammonification, nitrification and azofication.

2. To study the action of gypsum in soil and in solutions inoculated with pure cultures of *Bacillus radicola* isolated from alfalfa, Canada field peas, red clover and soybeans.

The first samples were drawn 15 days after the pots were filled. The surface soil was removed to a depth of five inches and the samples drawn with a sterile spatula. The surface soil was then replaced in the various pots, the samples were brought to the laboratory, and the moisture content, total nitrogen and nitrates determined in each case.

*A. Ammonification*

One hundred grams of each soil were put in duplicate tumblers and 5 gm. of dried blood added to each and stirred in thoroughly. The moisture content was brought up to the optimum, allowing 12 cc. for the dried blood used. The tumblers were incubated at room temperature for a period of 7 days. Ammonia was determined by the aeration method, potassium carbonate being used.

*B. Nitrification*

One-hundred-gram quantities of each soil were weighed out in duplicate tumblers and 100 mgm. of ammonium sulfate in solution added. The moisture content was adjusted to the optimum. The tumblers were covered and incubated for 5 weeks at room temperature, the moisture content being adjusted to the optimum every seventh day. The nitrates present at the end of the 5-week period were determined by the phenol-disulfonic acid method.

*C. Azofication*

One-hundred-gram quantities of soil were weighed out in duplicate tumblers and 5 gm. of dextrose added to each and thoroughly mixed in. The moisture content was made up to the optimum and the soils incubated at room temperature for a period of 10 days. At the end of that time the total nitrogen present was determined in duplicate by the Kjeldahl method, and the nitrogen content at the beginning subtracted from this gave the amount of nitrogen fixed.

*D. The effect of gypsum on radicola*

In order to study the effect of gypsum on the azofying power of pure cultures of *B. radicola* from alfalfa, field peas, red clover and soybeans, the following method was employed:

One-hundred-gram quantities of soil with various additions of gypsum were put into tumblers. One set of these tumblers was sterilized and the other was not. Both sets of tumblers were inoculated with pure cultures of *B. radiculicola* from red clover. After incubating for a period of 10 days the amount of nitrogen fixed was determined. Other sets of tumblers were arranged as previously and inoculated, respectively, with pure cultures of *B. radiculicola* from alfalfa, Canada field peas, red clover and soybeans in unsterilized soil alone. In each case the nitrogen fixed was determined.

One hundred cc. of "radiculicola solution"<sup>3</sup> was put into 500-cc. flasks, various amounts of gypsum added, sterilized and inoculated with pure cultures of *B. radiculicola* from different legumes. The nitrogen fixed in each case was determined by duplicate analyses.

#### *Crop tests*

After the plants in the pots had grown to maturity, the dry weight of straw and seed together was determined.

#### *Plant-food tests*

The acidity of the soil after the crops were harvested was determined by the modified Tacke method and reported in terms of tons of limestone required per acre.

In order to test the solubility of potash and the increase of the nitrogen content in the soil and in the crop, an experiment was arranged in the greenhouse. Sixty-four pots, each containing 10 pounds of Miami silt loam soil, were prepared and the same applications of gypsum and lime as in the previous experiment were made. These pots were sown to alfalfa, field peas, red clover and soybeans. Just before sowing, the seeds were inoculated with pure cultures of *B. radiculicola*. The moisture content of the pots was kept up to 15 per cent. At the end of the experiment the crops were harvested, dried and weighed. They were ground finely and determinations of total nitrogen and potassium were made in duplicates. The total nitrogen content of the soil was determined by the usual Kjeldahl method,  $\text{CuSO}_4$  and  $\text{K}_2\text{SO}_4$  being used for the digestion with  $\text{H}_2\text{SO}_4$ , with the aeration method of distillation.

In order to determine the water-soluble potassium, 100 gm. of soil was shaken with 200 cc. of distilled water for 4 hours in a mechanical shaker. The clear, supernatant liquid was filtered and aliquot portions of the filtrate were taken to determine the soluble potassium. The fusion for total potassium

<sup>3</sup> Radiculicola solution—

Dissolve in 1000 cc. of tap water,  
10 gm. saccharose  
1 gm.  $\text{K}_2\text{HPO}_4$

Stir until dissolved. Neutralize, using phenolphthalein as indicator. Sterilize in the autoclave at 15 pounds pressure for 15 minutes.

was accomplished according to the method of J. Laurence Smith for total alkali. Potassium was precipitated as the platonic chloride without previous removal of calcium, which was subsequently removed by washing with acidulated alcohol (33). Potassium was weighed as potassium platonic chloride in the case of the water-soluble as well as in the case of total potassium.

#### THE BACTERIOLOGICAL RESULTS

##### *Ammonification, nitrification and azofication*

The results of the tests of ammonification, nitrification and azofication at the first sampling are given in table 2.

TABLE 2  
*Effect of CaSO<sub>4</sub> on ammonification, nitrification and azofication—Sampling 1*

NUMBER	POUNDS OF CaSO <sub>4</sub> AND TONS OF CaCO <sub>3</sub> PER ACRE	AMMONIFICATION		NITRIFICATION		AZOFICATION	
		NH <sub>4</sub> nitrogen in 100 gm. of air-dry soil	Average	NO <sub>3</sub> nitrogen in 100 gm. of air-dry soil	Average	Nitrogen fixed in 100 gm. of air-dry soil	Average
		mgm.	mgm.	mgm.	mgm.	mgm.	mgm.
1	None.....	130.7		10.60		1.50	
2	None.....	130.9	130.80	10.40	10.50	1.50	1.50
3	3½ tons CaCO <sub>3</sub> .....	150.7		16.56		4.50	
4	3½ tons CaCO <sub>3</sub> .....	150.0	150.35	16.56	16.56	4.50	4.50
5	100 pounds CaSO <sub>4</sub> .....	126.0		8.90		6.00	
6	100 pounds CaSO <sub>4</sub> .....	123.9	124.95	8.90	8.90	6.50	6.25
7	500 pounds CaSO <sub>4</sub> .....	129.1		9.30		4.00	
8	500 pounds CaSO <sub>4</sub> .....	130.4	129.75	9.30	9.30	4.00	4.00
9	1000 pounds CaSO <sub>4</sub> .....	62.6		10.55		4.00	
10	1000 pounds CaSO <sub>4</sub> .....	63.2	62.90	10.33	10.44	4.25	4.12
11	100 pounds CaSO <sub>4</sub> + 3½ tons CaCO <sub>3</sub> .....	72.4		17.41		10.00	
12	100 pounds CaSO <sub>4</sub> + 3½ tons CaCO <sub>3</sub> .....	71.3	71.85	17.20	17.30	11.50	10.75
13	500 pounds CaSO <sub>4</sub> + 3½ tons CaCO <sub>3</sub> .....	73.2		20.65		10.50	
14	500 pounds CaSO <sub>4</sub> + 3½ tons CaCO <sub>3</sub> .....	72.2	72.70	20.65	20.65	10.60	10.55
15	1000 pounds CaSO <sub>4</sub> + 3½ tons CaCO <sub>3</sub> .....	66.9		20.60		12.00	
16	1000 pounds CaSO <sub>4</sub> + 3½ tons CaCO <sub>3</sub> .....	66.3	66.60	20.60	20.60	12.50	12.25

Examining this table it is evident that the ammonification of dried blood was reduced by all the applications of gypsum, the greatest reduction occurring where the gypsum was applied at the rate of 1000 pounds per acre. The application of lime with the gypsum did not increase ammonification but, on the other hand, decreased it considerably. This effect of lime was hardly expected since the application of lime alone greatly stimulated ammonification.

Nitrification also was slightly reduced in the soils which received the various amounts of gypsum alone, but the process was increased considerably where

lime alone, or lime with gypsum was used, the gypsum and lime together showing a greater increase than the lime alone. This increase in nitrification from the use of lime bears out previous results which have shown that the nitrifying organisms are very sensitive to a lack of lime. The beneficial effect of gypsum with lime indicates that the effect of the material on nitrification may be changed from detrimental to desirable by applying it with lime.

There was a marked increase in the azofying power of the soil when gypsum alone was applied, the smallest application showing the greatest effect. When lime was added with the gypsum a still greater effect on azofication was evidenced, the largest amount in this case giving the greatest effect. Lime showed about the same influence as gypsum alone and the large increase with the two materials was evidently due to the gypsum. As in the case of nitrification, gypsum seemed to exert its largest influence on azofication when the acidity of the soil was neutralized with lime.

The results secured at the second sampling appear in table 3.

TABLE 3  
*Effect of  $\text{CaSO}_4$  on ammonification, nitrification and azofication—Sampling 2*

NUMBER	POUNDS OF $\text{CaSO}_4$ AND TONS OF $\text{CaCO}_3$ PER ACRE	AMMONIFICATION		NITRIFICATION		AZOFICATION	
		$\text{NH}_3$ nitrogen in 100 gm. of air-dry soil	Average	$\text{NO}_3$ nitrogen in 100 gm. of air-dry soil	Average	Nitrogen fixed in 100 gm. of air-dry soil	Average
		mgm.	mgm.	mgm.	mgm.	mgm.	mgm.
1	None .....	95.90		13.9		1.20	
2	None .....	97.30	96.60	13.9	13.90	1.20	1.20
3	$3\frac{1}{2}$ tons $\text{CaCO}_3$ .....	136.95		16.1		1.70	
4	$3\frac{1}{2}$ tons $\text{CaCO}_3$ .....	139.81	138.38	15.3	15.70	1.70	1.70
5	100 pounds $\text{CaSO}_4$ .....	84.15		12.2		4.70	
6	100 pounds $\text{CaSO}_4$ .....	94.71	89.43	12.2	12.20	4.30	4.50
7	500 pounds $\text{CaSO}_4$ .....	103.07		13.3		4.80	
8	500 pounds $\text{CaSO}_4$ .....	101.64	102.35	13.3	13.30	4.80	4.80
9	1000 pounds $\text{CaSO}_4$ .....	113.19		16.1		6.30	
10	1000 pounds $\text{CaSO}_4$ .....	114.07	113.63	16.7	16.40	6.30	6.30
11	100 pounds $\text{CaSO}_4$ + $3\frac{1}{2}$ tons $\text{CaCO}_3$ ..	153.35		17.2		9.55	
12	100 pounds $\text{CaSO}_4$ + $3\frac{1}{2}$ tons $\text{CaCO}_3$ ..	155.22	154.28	18.2	17.70	7.05	8.30
13	500 pounds $\text{CaSO}_4$ + $3\frac{1}{2}$ tons $\text{CaCO}_3$ ..	118.47		17.3		4.30	
14	500 pounds $\text{CaSO}_4$ + $3\frac{1}{2}$ tons $\text{CaCO}_3$ ..	113.08	115.77	17.3	17.30	4.30	4.30
15	1000 pounds $\text{CaSO}_4$ + $3\frac{1}{2}$ tons $\text{CaCO}_3$ ..	135.30		12.1		2.80	
16	1000 pounds $\text{CaSO}_4$ + $3\frac{1}{2}$ tons $\text{CaCO}_3$ ..	136.40	135.85	12.4	12.25	2.80	2.80

Examining this table it is found that the ammonification of dried blood was not affected by the small amounts of gypsum but the larger applications gave an increase which was quite pronounced with the largest amount. When lime was used with the gypsum, still larger increases were obtained, the

smallest amount of gypsum giving the greatest effect in this case. Lime alone brought about an increase just as it did in the first instance, and only in one case did the gypsum with lime show an increase over the lime alone.

Nitrification was increased in the soil that had received gypsum at the rate of 1000 pounds per acre. Smaller applications of the gypsum than this had no effect on the nitrifying organisms. Lime alone stimulated nitrification, and gypsum with lime gave a still greater stimulation on the activities of nitrifying organisms, except where the largest application of gypsum was made, in which case no effect of either material was noted.

Azofication was increased where gypsum alone was applied, the greatest increase occurring with the application of the largest amount of gypsum. Lime alone had a slight effect and gypsum with lime showed a greater effect than gypsum alone only with the 100-pound application. With the larger amounts the activities of azofying organisms were reduced.

It may be noted in this table that gypsum applied alone at the rate of 1000 pounds per acre increased the activities of the azofying and the nitrifying organisms, but when an application of lime was made with it these processes were decreased. On the other hand, lime applied with gypsum at the rate of 1000 pounds increased ammonification more than did the gypsum alone.

The results obtained at the third sampling are given in table 4.

TABLE 4  
*Effect of  $\text{CaSO}_4$  on ammonification, nitrification and azofication—Sampling 3*

NUMBER	POUNDS OF $\text{CaSO}_4$ AND TONS OF $\text{CaCO}_3$ PER ACRE	AMMONIFICATION		NITRIFICATION		AZOFICATION	
		$\text{NH}_4$ nitrogen in 100 gm. of air-dry soil	Average	$\text{NO}_3$ nitrogen in 100 gm. of air-dry soil	Average	Nitrogen fixed in 100 gm. of air-dry soil	Average
		mgm.	mgm.	mgm.	mgm.	mgm.	mgm.
1	None .....	132.7		18.0		2.75	
2	None .....	134.1	133.40	18.4	18.20	2.75	2.75
3	$3\frac{1}{2}$ tons $\text{CaCO}_3$ .....	167.5		24.5		2.25	
4	$3\frac{1}{2}$ tons $\text{CaCO}_3$ .....	158.2	162.85	24.5	24.50	2.25	2.25
5	100 pounds $\text{CaSO}_4$ .....	130.4		20.6		4.75	
6	100 pounds $\text{CaSO}_4$ .....	131.3	130.85	20.7	20.65	4.75	4.75
7	500 pounds $\text{CaSO}_4$ .....	129.4		14.4		1.75	
8	500 pounds $\text{CaSO}_4$ .....	127.1	128.25	14.4	14.40	1.75	1.75
9	1000 pounds $\text{CaSO}_4$ .....	135.1		15.3		2.25	
10	1000 pounds $\text{CaSO}_4$ .....	135.8	135.45	15.3	15.30	2.25	2.25
11	100 pounds $\text{CaSO}_4$ + $3\frac{1}{2}$ tons $\text{CaCO}_3$ ..	141.0		16.7		3.75	
12	100 pounds $\text{CaSO}_4$ + $3\frac{1}{2}$ tons $\text{CaCO}_3$ ..	142.2	141.60	17.3	17.00	3.25	3.50
13	500 pounds $\text{CaSO}_4$ + $3\frac{1}{2}$ tons $\text{CaCO}_3$ ..	148.8		16.2		3.00	
14	500 pounds $\text{CaSO}_4$ + $3\frac{1}{2}$ tons $\text{CaCO}_3$ ..	147.9	148.35	16.2	16.20	3.75	3.37
15	1000 pounds $\text{CaSO}_4$ + $3\frac{1}{2}$ tons $\text{CaCO}_3$ ..	158.1		15.5		9.75	
16	1000 pounds $\text{CaSO}_4$ + $3\frac{1}{2}$ tons $\text{CaCO}_3$ ..	158.5	158.30	15.6	15.55	9.75	9.75

The gypsum applied at the rate of 1000 pounds per acre showed a slight increase in the ammonification of dried blood while the smaller applications had no effect. Lime alone increased ammonification and when the two materials were used together, the ammonifying power of the soil was increased but the increase was smaller than when the lime was applied alone.

At this sampling, gypsum did not have any pronounced effect on nitrification except when applied at the rate of 100 pounds per acre, when a slight increase in nitrification occurred. Lime alone increased nitrification but when used with gypsum there was no effect evidenced on the process, the nitrifying power being actually lower than in the check soil.

There was a marked increase in the azofying power of the soil when gypsum was applied at the rate of 100 pounds per acre, but the larger applications had no effect whatever.

Lime alone had no effect on this process but, when used with gypsum increases were obtained in every case, the greatest increase occurring when the gypsum was applied at the rate of 1000 pounds per acre.

The results of the tests of ammonification, nitrification and azofication at the fourth sampling are given in table 5.

TABLE 5  
*Effect of  $\text{CaSO}_4$  on ammonification, nitrification and azofication—Sampling 4*

NUMBER	POUNDS OF $\text{CaSO}_4$ AND TONS OF $\text{CaCO}_3$ PER ACRE	AMMONIFICATION		NITRIFICATION		AZOFICATION	
		NH <sub>3</sub> nitrogen in 100 gm. of air-dry soil	Average	NO <sub>3</sub> nitrogen in 100 gm. of air-dry soil	Average	Nitrogen fixed in 100 gm. of air-dry soil	Average
		mgm.	mgm.	mgm.	mgm.	mgm.	mgm.
1	None .....	126.85		14.67		2.90	
2	None .....	125.67	126.26	14.67	14.67	2.90	2.90
3	$3\frac{1}{2}$ tons $\text{CaCO}_3$ .....	152.45		21.84		5.60	
4	$3\frac{1}{2}$ tons $\text{CaCO}_3$ .....	151.15	151.80	21.87	21.87	5.60	5.60
5	100 pounds $\text{CaSO}_4$ .....	121.42		12.27		10.60	
6	100 pounds $\text{CaSO}_4$ .....	119.88	120.65	12.27	12.27	8.60	9.60
7	500 pounds $\text{CaSO}_4$ .....	123.78		12.45		2.60	
8	500 pounds $\text{CaSO}_4$ .....	124.84	124.31	12.30	12.37	2.60	2.60
9	1000 pounds $\text{CaSO}_4$ .....	116.58		9.05		2.40	
10	1000 pounds $\text{CaSO}_4$ .....	111.94	114.26	9.05	9.05	2.90	2.65
11	100 pounds $\text{CaSO}_4 + 3\frac{1}{2}$ tons $\text{CaCO}_3$ ..	128.62		13.10		6.10	
12	100 pounds $\text{CaSO}_4 + 3\frac{1}{2}$ tons $\text{CaCO}_3$ ..	129.47	129.04	12.84	12.97	6.60	6.35
13	500 pounds $\text{CaSO}_4 + 3\frac{1}{2}$ tons lime .....	168.62		13.55		6.60	
14	500 pounds $\text{CaSO}_4 + 3\frac{1}{2}$ tons lime .....	167.67	168.14	14.00	13.77	6.60	6.60
15	1000 pounds $\text{CaSO}_4 + 3\frac{1}{2}$ tons $\text{CaCO}_3$ ..	156.35		18.03		3.60	
16	1000 pounds $\text{CaSO}_4 + 3\frac{1}{2}$ tons $\text{CaCO}_3$ ..	155.52	155.93	17.90	17.96	3.10	3.35

Examining this table it is evident that the ammonifying power of the soil organisms was slightly decreased by all the applications of gypsum. Lime

alone and lime applied with gypsum in the various amounts increased ammonification, the greatest increase occurring when the gypsum was applied at the rate of 500 pounds per acre.

Gypsum applied alone decreased nitrification, the greatest decrease occurring with the application of 1000 pounds per acre. Lime alone increased the process, but lime with gypsum showed no effect except where the largest amounts of gypsum per acre were used, when a distinct increase occurred.

Azofication was greatly increased with the application of gypsum at the rate of 100 pounds per acre, but the larger amounts showed no effect whatever. Lime increased the process and lime with the various applications of gypsum also showed an increase over the check soil in all cases and over the limed soil in all cases except where the largest amount of gypsum was used.

On the whole, the results obtained at this sampling show no effect from the applications of gypsum alone and when used with lime the increases were generally less than those secured with lime alone. Only in the case of ammonification were the increases from the two materials greater than from the lime alone.

The results secured at the fifth sampling are given in table 6.

TABLE 6  
*Effect of CaSO<sub>4</sub> on ammonification, nitrification and azofication—Sampling 5*

NUMBER	POUNDS OF CaSO <sub>4</sub> AND TONS OF CaCO <sub>3</sub> PER ACRE	AMMONIFICATION		NITRIFICATION		AZOFICATION	
		NH <sub>4</sub> nitrogen in 100 gm. of air-dry soil	Average	NO <sub>3</sub> nitrogen in 100 gm. of air-dry soil	Average	Nitrogen fixed in 100 gm. of air-dry soil	Average
		mgm.	mgm.	mgm.	mgm.	mgm.	mgm.
1	None.....	134.52		12.1		2.0	
2	None.....	134.52	134.52	12.5	12.30	2.0	2.0
3	3½ tons CaCO <sub>3</sub> .....	203.55		17.4		4.5	
4	3½ tons CaCO <sub>3</sub> .....	202.60	203.07	17.6	17.50	4.5	4.5
5	100 pounds CaSO <sub>4</sub> .....	142.89		9.9		1.5	
6	100 pounds CaSO <sub>4</sub> .....	142.07	142.48	9.3	9.60	1.5	1.5
7	500 pounds CaSO <sub>4</sub> .....	143.96		6.7		2.0	
8	500 pounds CaSO <sub>4</sub> .....	142.78	143.37	7.7	7.20	2.0	2.0
9	1000 pounds CaSO <sub>4</sub> .....	136.40		10.5		3.5	
10	1000 pounds CaSO <sub>4</sub> .....	136.76	136.58	10.3	10.40	3.5	3.5
11	100 pounds CaSO <sub>4</sub> + 3½ tons CaCO <sub>3</sub> ..	209.09		15.5		6.5	
12	100 pounds CaSO <sub>4</sub> + 3½ tons CaCO <sub>3</sub> ..	209.80	209.44	15.4	15.45	6.5	6.5
13	500 pounds CaSO <sub>4</sub> + 3½ tons CaCO <sub>3</sub> ..	207.44		15.7		8.5	
14	500 pounds CaSO <sub>4</sub> + 3½ tons CaCO <sub>3</sub> ..	206.73	207.08	16.3	16.00	8.5	8.5
15	1000 pounds CaSO <sub>4</sub> + 3½ tons CaCO <sub>3</sub> ..	172.75		15.0		5.5	
16	1000 pounds CaSO <sub>4</sub> + 3½ tons CaCO <sub>3</sub> ..	172.28	172.51	14.4	14.70	5.5	5.5

Gypsum applications increased ammonification, the smallest increase occurring when the gypsum was applied at the rate of 1000 pounds per acre.

Lime alone increased the process and when applied with gypsum a still greater effect was noted except where the 1000-pound application of gypsum was made.

Nitrification was decreased with all the applications of gypsum alone, but when the gypsum was applied with lime, increases were secured which were smaller, however, than that brought about by the lime alone.

Azofication was not affected by the smaller applications of gypsum, but the largest amount increased the process slightly. When used with lime, however, distinct increases were obtained, all of which were greater than that given by the use of lime alone.

At this sampling gypsum alone showed an influence only in the ammonification process but when used with lime distinct increases were shown in azofication also. The nitrification process was affected less by the two materials together than by the lime alone.

The results obtained at the sixth sampling appear in table 7.

TABLE 7  
*Effect of  $\text{CaSO}_4$  on ammonification, nitrification and azofication—Sampling 6*

NUMBER	POUNDS OF $\text{CaSO}_4$ AND TONS OF $\text{CaCO}_3$ PER ACRE	AMMONIFICATION		NITRIFICATION		AZOFICATION	
		$\text{NH}_4$ nitrogen in 100 gm. of air-dry soil	Average	$\text{NO}_3$ nitrogen in 100 gm. of air-dry soil	Average	Nitrogen fixed in 100 gm. of air-dry soil	Average
		mgm.	mgm.	mgm.	mgm.	mgm.	mgm.
1	None .....	136.76		9.4		3.0	
2	None .....	132.04	134.40	9.4	9.40	3.0	3.0
3	$3\frac{1}{2}$ tons $\text{CaCO}_3$ .....	211.20		14.6		5.0	
4	$3\frac{1}{2}$ tons $\text{CaCO}_3$ .....	211.20	211.20	16.0	15.30	5.0	5.0
5	100 pounds $\text{CaSO}_4$ .....	120.95		10.4		3.0	
6	100 pounds $\text{CaSO}_4$ .....	120.59	120.77	11.4	10.90	3.0	3.0
7	500 pounds $\text{CaSO}_4$ .....	134.28		8.0		2.0	
8	500 pounds $\text{CaSO}_4$ .....	133.57	133.92	9.1	8.55	2.0	2.0
9	1000 pounds $\text{CaSO}_4$ .....	121.54		8.5		1.0	
10	1000 pounds $\text{CaSO}_4$ .....	124.49	123.01	8.0	8.25	1.0	1.0
11	100 pounds $\text{CaSO}_4$ + $3\frac{1}{2}$ tons $\text{CaCO}_3$ ..	198.12		14.0		14.5	
12	100 pounds $\text{CaSO}_4$ + $3\frac{1}{2}$ tons $\text{CaCO}_3$ ..	193.28	195.70	14.3	14.15	14.5	14.5
13	500 pounds $\text{CaSO}_4$ + $3\frac{1}{2}$ tons $\text{CaCO}_3$ ..	204.02		12.6		6.5	
14	500 pounds $\text{CaSO}_4$ + $3\frac{1}{2}$ tons $\text{CaCO}_3$ ..	207.32	205.67	12.6	12.60	6.5	6.5
15	1000 pounds $\text{CaSO}_4$ + $3\frac{1}{2}$ tons $\text{CaCO}_3$ ..	192.69		13.6		5.0	
16	1000 pounds $\text{CaSO}_4$ + $3\frac{1}{2}$ tons $\text{CaCO}_3$ ..	195.29	193.99	13.6	13.60	5.0	5.0

Ammonification was decreased at this sampling by all the applications of gypsum, the greatest decrease occurring with the smallest application. Lime alone showed an increase in ammonification and gypsum with lime also showed a considerable increase over the check soil, but a smaller effect than the lime alone.

Nitrification was also decreased by gypsum alone, except with the 100-pound application, but when lime was used with the gypsum the process was stimulated. The greatest increase in nitrification, however, was secured, as in the case of ammonification, by the application of lime alone.

Azofication was decreased by the larger applications of gypsum, while the application of 100 pounds per acre had no effect. When used with lime distinct increases in azofication were secured, the greatest increase occurring with the smallest amount of gypsum. In every case the two materials showed a greater effect than the lime alone.

At this sampling gypsum alone did not increase the process of ammonification, nitrification and azofication, but in most cases showed slight decreases. When used with lime, however, there were obtained increases in azofication greater than from lime alone. Nitrification and ammonification were not thus affected.

#### EFFECT OF GYPSUM ON *B. RADICICOLA*

The results of the tests of the quantities of nitrogen fixed by the pure culture of *B. radiculicola* from the nodules of red clover appear in table 8.

TABLE 8

*Effect of sterilization of the soil on azofication by B. radiculicola from red clover and on nitrification*

NUMBER	POUNDS OF $\text{CaSO}_4$ AND TONS OF $\text{CaCO}_3$ PER ACRE	UNSTERILIZED SOIL		STERILIZED SOIL	
		Azofication		Azofication	
		Nitrogen fixed in 100 gm. of soil	Average	Nitrogen fixed in 100 gm. of soil	Average
		mgm.	mgm.	mgm.	mgm.
1	None.....	9.25		4.75	
2	None.....	12.25	10.75	5.25	5.00
3	$3\frac{1}{2}$ tons $\text{CaCO}_3$ .....	9.75		11.25	
4	$3\frac{1}{2}$ tons $\text{CaCO}_3$ .....	10.25	10.00	16.75	14.00
5	500 pounds $\text{CaSO}_4$ .....	11.25		9.25	
6	500 pounds $\text{CaSO}_4$ .....	8.25	9.75	12.25	10.75
7	500 pounds $\text{CaSO}_4$ + $3\frac{1}{2}$ tons $\text{CaCO}_3$ .....	14.25		9.25	
8	500 pounds $\text{CaSO}_4$ + $3\frac{1}{2}$ tons $\text{CaCO}_3$ .....	18.75	16.50	11.75	10.50

The amount of nitrogen fixed by *B. radiculicola* in the unsterilized soil was somewhat reduced by the gypsum while the lime brought about practically no effect. The two materials together, however, gave a decided increase. In the sterilized soil both lime and gypsum increased the fixation of nitrogen, the lime giving the greater effect. The influence of the two materials in this case, however, was no greater than the effect of gypsum alone and was smaller than the effect of the lime alone.

The results secured on the amounts of nitrogen fixed by *B. radicola* from alfalfa, field peas, red clover and soybeans are given in table 9.

TABLE 9  
*Soil studies on the azofication by B. radicola, strains of alfalfa, field peas, red clover and soybeans*

NUMBER	POUNDS OF $\text{CaSO}_4$ AND TONS OF $\text{CaCO}_3$ PER ACRE	ALFALFA		FIELD PEAS		RED CLOVER		SOYBEANS	
		Nitrogen fixed in 100 gm. of soil	Average	Nitrogen fixed in 100 gm. of soil	Average	Nitrogen fixed in 100 gm. of soil	Average	Nitrogen fixed in 100 gm. of soil	Average
		mgm.	mgm.	mgm.	mgm.	mgm.	mgm.	mgm.	mgm.
1	None .....	1.15		4.25		0.25		6.75	
2	None .....	1.15	1.15	4.25	4.25	0.25	0.25	6.75	6.75
3	$3\frac{1}{2}$ tons $\text{CaCO}_3$ .....	4.25		3.75		2.75		4.75	
4	$3\frac{1}{2}$ tons $\text{CaCO}_3$ .....	4.25	4.25	3.75	3.75	2.25	2.50	4.75	4.75
5	100 pounds $\text{CaSO}_4$ .....	4.25		3.75		1.75		3.75	
6	100 pounds $\text{CaSO}_4$ .....	4.25	4.25	3.75	3.75	1.75	1.75	3.75	3.75
7	500 pounds $\text{CaSO}_4$ .....	4.25		9.25		1.75		7.75	
8	500 pounds $\text{CaSO}_4$ .....	4.25	4.25	11.25	10.75	1.75	1.75	7.75	7.75
9	1000 pounds $\text{CaSO}_4$ .....	6.75		8.75		4.25		6.25	
10	1000 pounds $\text{CaSO}_4$ .....	6.75	6.75	8.75	8.75	4.25	4.25	6.25	6.25
11	100 pounds $\text{CaSO}_4 + 3\frac{1}{2}$ tons $\text{CaCO}_3$ .....	6.25		6.75		2.25		7.75	
12	100 pounds $\text{CaSO}_4 + 3\frac{1}{2}$ tons $\text{CaCO}_3$ .....	5.75	6.00	6.75	6.75	2.75	2.50	7.75	7.75
13	500 pounds $\text{CaSO}_4 + 3\frac{1}{2}$ tons $\text{CaCO}_3$ .....	4.25		6.25		4.75		8.25	
14	500 pounds $\text{CaSO}_4 + 3\frac{1}{2}$ tons $\text{CaCO}_3$ .....	4.25	4.25	6.25	6.25	4.75	4.75	8.25	8.25
15	1000 pounds $\text{CaSO}_4 + 3\frac{1}{2}$ tons $\text{CaCO}_3$ .....	4.25		6.25		3.25		6.25	
16	1000 pounds $\text{CaSO}_4 + 3\frac{1}{2}$ tons $\text{CaCO}_3$ .....	4.25	4.25	6.25	6.25	3.25	3.25	6.25	6.25

Observing the table, it is found that the amount of nitrogen fixed by the organisms from alfalfa was increased by the application of gypsum to the soil, the 100-pound and 500-pound applications showing the same effect while the 1000-pound amount gave a greater effect. The lime showed about the same influence as the smaller amounts of gypsum and the two materials together no effect on the single application except with the 100-pound application when a slight gain was noted. In the case of the organism from the field peas the lime and smallest amount of gypsum had no effect, but the larger amounts of gypsum showed a distinct increase. The two materials together had less effect than the gypsum alone except in the case of smallest amount.

The organism from red clover produced an increase in nitrogen-fixing power by both lime and gypsum, the largest amount showing the greatest effect. With the two materials together, slightly greater effects were noted except in one case.

The soybean organism was reduced in fixing power by the lime and 100 pounds of gypsum, but the larger amounts of gypsum had little effect. The two materials together had little effect over the gypsum alone except with the smallest amount when a gain was noted.

It is evident from these results in general that the amount of nitrogen fixed by *B. radiculicola* was increased when the larger quantities of gypsum were applied; the smaller amounts frequently showing a decrease. An application of lime with gypsum did not seem to have any pronounced effect on the nitrogen fixed and indeed, in several cases, lime with large amounts of gypsum actually decreased the amount of nitrogen fixed when compared with the effects of large amounts of gypsum applied alone.

The results secured on the nitrogen fixed by *B. radiculicola* in solution tests with various amounts of gypsum applied, appear in table 10.

TABLE 10  
Solution studies on the azofication by *B. radiculicola*, strains of alfalfa, field peas, red clover and soybeans

NUMBER	POUNDS OF $\text{CaSO}_4$ AND TONS OF $\text{CaCO}_3$ PER ACRE	ALFALFA		CANADA FIELD PEAS		RED CLOVER		SOYBEANS	
		Nitrogen fixed per 100 cc. of solution	Average	Nitrogen fixed per 100 cc. of solution	Average	Nitrogen fixed per 100 cc. of solution	Average	Nitrogen fixed per 100 cc. of solution	Average
		mgm.	mgm.	mgm.	mgm.	mgm.	mgm.	mgm.	mgm.
1	None .....	2.5		2.7		2.5		1.8	
2	None .....	2.6	2.56	2.0	2.35	2.5	2.50	2.0	1.90
3	2 tons $\text{CaCO}_3$ .....	2.8		1.7		2.3		1.8	
4	2 tons $\text{CaCO}_3$ .....	2.9	2.85	1.9	1.80	2.3	2.30	1.7	1.75
5	100 pounds $\text{CaSO}_4$ .....	2.2		2.2		1.8		2.0	
6	100 pounds $\text{CaSO}_4$ .....	2.2	2.20	2.1	2.15	1.4	1.60	2.9	2.45
7	500 pounds $\text{CaSO}_4$ .....	2.6		2.4		2.0		2.9	
8	500 pounds $\text{CaSO}_4$ .....	2.5	2.55	1.8	2.10	2.0	2.00	2.3	2.60
9	1000 pounds $\text{CaSO}_4$ .....	3.0		2.0		2.5		2.9	
10	1000 pounds $\text{CaSO}_4$ .....	2.8	2.90	4.4	3.20	2.4	2.45	3.0	2.95
11	100 pounds $\text{CaSO}_4$ + 2 tons $\text{CaCO}_3$ .....	2.7		2.5		1.3		2.2	
12	100 pounds $\text{CaSO}_4$ + 2 tons $\text{CaCO}_3$ .....	3.0	2.85	2.4	2.45	1.3	1.30	2.5	2.35
13	500 pounds $\text{CaSO}_4$ + 2 tons $\text{CaCO}_3$ .....	2.4		2.5		2.9		2.6	
14	500 pounds $\text{CaSO}_4$ + 2 tons $\text{CaCO}_3$ .....	2.6	2.50	2.4	2.45	1.8	2.85	2.5	2.55
15	1000 pounds $\text{CaSO}_4$ + 2 tons $\text{CaCO}_3$ .....	2.8		2.5		1.6		2.1	
16	1000 pounds $\text{CaSO}_4$ + 2 tons $\text{CaCO}_3$ .....	3.0	2.90	2.3	2.40	1.8	1.70	1.9	2.00

Examining this table it is found that there was no marked increase or decrease in the amounts of nitrogen fixed by any of the cultures either with the application of gypsum alone or with the addition of gypsum and lime

together. In a few cases slight increases in the amounts of nitrogen fixed were obtained where the largest amounts of gypsum were applied, but the influence in these cases was not great.

The amounts of nitrogen fixed by *B. radiculicola* were much greater in the soil than in the solution, which fact is very likely due to the differences in the soil and the solution as a medium for the growth of these organisms. The liquid medium is hardly as satisfactory for the study of the activities of soil microorganisms, since aeration conditions are generally unsatisfactory for their best activities.

## CROP RESULTS

The results of the crop tests of clover and wheat appear in table 11.

TABLE 11  
Crop yields—dry weight

NUMBER	POUNDS OF $\text{CaSO}_4$ AND TONS OF $\text{CaCO}_3$ PER ACRE	WHEAT		CLOVER	
		Dry weight per pot	Average	Dry weight per pot	Average
		gm.	gm.	gm.	gm.
1	None.....	60.00		80.00	
2	None.....	70.00	65.00	70.00	75.00
3	$3\frac{1}{2}$ tons $\text{CaCO}_3$ .....	94.50		120.00	
4	$3\frac{1}{2}$ tons $\text{CaCO}_3$ .....	116.50	105.50	123.00	121.50
5	100 pounds $\text{CaSO}_4$ .....	64.00		70.00	
6	100 pounds $\text{CaSO}_4$ .....	67.00	65.50	72.00	71.00
7	500 pounds $\text{CaSO}_4$ .....	68.00		73.00	
8	500 pounds $\text{CaSO}_4$ .....	69.00	68.50	78.00	75.50
9	1000 pounds $\text{CaSO}_4$ .....	69.00		134.00	
10	1000 pounds $\text{CaSO}_4$ .....	64.00	66.50	131.00	132.50
11	100 pounds $\text{CaSO}_4 + 3\frac{1}{2}$ tons $\text{CaCO}_3$ .....	86.00		115.00	
12	100 pounds $\text{CaSO}_4 + 3\frac{1}{2}$ tons $\text{CaCO}_3$ .....	89.00	87.50	111.00	113.00
13	500 pounds $\text{CaSO}_4 + 3\frac{1}{2}$ tons $\text{CaCO}_3$ .....	70.50		120.00	
14	500 pounds $\text{CaSO}_4 + 3\frac{1}{2}$ tons $\text{CaCO}_3$ .....	78.00	74.25	127.00	123.50
15	1000 pounds $\text{CaSO}_4 + 3\frac{1}{2}$ tons $\text{CaCO}_3$ .....	80.00		125.00	
16	1000 pounds $\text{CaSO}_4 + 3\frac{1}{2}$ tons $\text{CaCO}_3$ .....	78.00	79.00	122.00	123.50

Observing the results given in this table it is evident that the application of gypsum alone did not show any effect on the yield of wheat, but the largest application of gypsum greatly increased the yield of red clover. Lime alone increased the yield of the wheat crop considerably, but when applied with gypsum the increase was much smaller; the effect was greater, however, than where gypsum was used alone. Lime alone and lime with gypsum increased the yields of the red clover crop, but in no case was the increase quite as great as when gypsum was applied alone at the rate of 1000 pounds per acre.

Examining the crop yields obtained in tables 13, 14, 15 and 16, it is still more evident that the gypsum applications did not increase to any marked

extent the yields of alfalfa, field peas, red clover and soybeans, when these crops were inoculated with the proper cultures of *B. radicicola*.

Taking the crop results as a whole, it is evident that applications of gypsum had very little effect, if any, on wheat or leguminous crops grown on Miami silt loam soil.

#### THE AVAILABILITY OF PLANT-FOODS

The results obtained on the acidity of the soil and on the production of water-soluble potassium are given in table 12.

TABLE 12  
*Acidity and soluble potassium*

NUMBER	POUNDS OF $\text{CaSO}_4$ AND TONS OF $\text{CaCO}_3$ PER ACRE	ACIDITY		WATER-SOLUBLE POTASSIUM			
		CaCO <sub>3</sub> required to correct acidity of an acre	Average	Per cent	Average per cent	Amount per acre	Average amount per acre
		lbs.	lbs.			lbs.	lbs.
1	None .....	600		0.0037		74	
2	None .....	675	637	0.0037	0.0037	74	74
3	$3\frac{1}{2}$ tons $\text{CaCO}_3$ .....	None		0.0075		150	
4	$3\frac{1}{2}$ tons $\text{CaCO}_3$ .....	None		0.0077	0.0076	154	152
5	100 pounds $\text{CaSO}_4$ .....	1625		0.0036		72	
6	100 pounds $\text{CaSO}_4$ .....	1625	1625	0.0036	0.0036	72	72
7	500 pounds $\text{CaSO}_4$ .....	1875		0.0020		40	
8	500 pounds $\text{CaSO}_4$ .....	1850	1862	0.0020	0.0020	40	40
9	1000 pounds $\text{CaSO}_4$ .....	1900		0.0048		96	
10	1000 pounds $\text{CaSO}_4$ .....	1900	1900	0.0047	0.0047	94	95
11	100 pounds $\text{CaSO}_4$ + $3\frac{1}{2}$ tons $\text{CaCO}_3$ ..	125		0.0099		198	
12	100 pounds $\text{CaSO}_4$ + $3\frac{1}{2}$ tons $\text{CaCO}_3$ ..	100	112	0.0099	0.0099	198	198
13	500 pounds $\text{CaSO}_4$ + $3\frac{1}{2}$ tons $\text{CaCO}_3$ ..	50		0.0098		196	
14	500 pounds $\text{CaSO}_4$ + $3\frac{1}{2}$ tons $\text{CaCO}_3$ ..	200	125	0.0095	0.0096	190	193
15	1000 pounds $\text{CaSO}_4$ + $3\frac{1}{2}$ tons $\text{CaCO}_3$ ..	25		0.0093		186	
16	1000 pounds $\text{CaSO}_4$ + $3\frac{1}{2}$ tons $\text{CaCO}_3$ ..		125	0.0090	0.0091	180	183

Observing these results it is found that the acidity of the soil was increased by the application of gypsum, the larger amount giving the greatest increase. Beyond 500 pounds per acre, however, there seemed to be little additional influence on the acidity. The acidity in the untreated soil was much less than when the experiment was begun, probably because of the alkalinity of the tap water used on the soil.

The production of water-soluble potassium in the soil was apparently not affected by the use of smaller amounts of gypsum, but there was a slight increase when 1000 pounds were used. With the 500-pound application there was a slight decrease but the difference was not great. The application of lime alone and lime with gypsum increased considerably the production of

soluble potassium, the greatest increase occurring when the smallest amount of gypsum was used, but the difference here was not great. Gypsum and lime together seemed to exert a greater effect than lime alone.

The effects of gypsum on the production of soluble potassium, on the total nitrogen content of the soil and on the total potassium and total nitrogen in alfalfa are shown in table 13.

TABLE 13

*Effects of gypsum on the solubility of potassium and on the total nitrogen content of the inoculated soil and crop of alfalfa*

NUMBER	GYPSUM (CaSO <sub>4</sub> ) PER ACRE	LIMESTONE (CaCO <sub>3</sub> ) PER ACRE	CROP						SOIL					
			Crop yields		Total nitrogen		Total potassium		Total nitrogen		Water-soluble potassium			
			Per pot	Average	Per cent nitrogen	Average per cent	Per cent potassium	Average per cent	Nitrogen per 100 gm. of soil	Average	Per cent potassium	Average per cent	Pounds per acre	Average pounds per acre
	lbs.	tons	gm.	gm.					mgm.	mgm.				
1	Nil	Nil	3.25		3.08		1.41		93		0.0029		57.80	
2	Nil	Nil			3.30		1.33		93		0.0016		32.16	
3	Nil	Nil	3.30		3.60		1.44		93		0.0022		45.02	
4	Nil	Nil		3.27	3.60	3.39	1.22	1.35	93	93	0.0022	0.0022	45.02	45.00
5	Nil	3 $\frac{1}{4}$	3.30		3.10		1.30		87		0.0029		57.80	
6	Nil	3 $\frac{1}{4}$			3.20		1.27		87		0.0016		32.16	
7	Nil	3 $\frac{1}{4}$	3.00		2.98		1.06		89		0.0016		32.16	
8	Nil	3 $\frac{1}{4}$		3.15	3.20	3.12	1.09	1.18	89	88	0.0012	0.0018	25.72	36.96
9	100	Nil	3.75		3.48		1.42		93		0.0029		57.80	
10	100	Nil			3.60		1.49		93		0.0022		45.02	
11	100	Nil	2.50		3.60		1.39		93		0.0032		64.32	
12	100	Nil		3.12	3.60	3.57	1.36	1.41	93	93	0.0032	0.0029	64.32	57.86
13	500	Nil	2.50		3.76		1.56		98		0.0016		32.16	
14	500	Nil			3.76		1.41		90		0.0029		57.80	
15	500	Nil	3.25		3.62		1.44		93		0.0029		57.80	
16	500	Nil		2.87	3.62	3.69	1.52	1.48	94	94	0.0025	0.0025	51.45	49.80
17	1000	Nil	3.75		3.54		1.43		93		0.0012		25.72	
18	1000	Nil			4.06		1.06		93		0.0019		38.59	
19	1000	Nil	4.00		3.66		1.22		92		0.0045		90.04	
20	1000	Nil		3.50	3.66	3.73	0.99	1.17	106	96	0.0054	0.0032	109.34	65.92
21	100	3 $\frac{1}{4}$	5.40		3.64		0.83		92		0.0041		83.61	
22	100	3 $\frac{1}{4}$			3.64		0.80		95		0.0041		83.61	
23	100	3 $\frac{1}{4}$	4.25		3.16		0.67		93		0.0016		32.16	
24	100	3 $\frac{1}{4}$		4.70	3.50	3.48	0.73	0.76	92	93	0.0016	0.0028	32.16	57.88
25	500	3 $\frac{1}{4}$	3.25		3.60		0.98		93		0.0016		32.16	
26	500	3 $\frac{1}{4}$			3.50		0.94		93		0.0019		38.59	
27	500	3 $\frac{1}{4}$	4.50		3.24		0.70		116		0.0029		57.80	
28	500	3 $\frac{1}{4}$		3.75	3.10	3.36	0.73	0.84	116	104	0.0025	0.0022	51.45	45.00
29	1000	3 $\frac{1}{4}$	5.50		4.24		0.95		95		0.0019		38.59	
30	1000	3 $\frac{1}{4}$			4.14		0.95		94		0.0012		25.72	
31	1000	3 $\frac{1}{4}$	3.00		3.72		0.90		93		0.0029		57.80	
32	1000	3 $\frac{1}{4}$		4.25	3.76	3.96	0.90	0.87		94	0.0029	0.0022	57.80	44.98

Examining this table it is quite evident that there was little effect on the crop yields; slight increases were noted when gypsum and lime were applied together. The total nitrogen and total potassium content of the crop was not affected by the application of gypsum.

The total nitrogen content of the soil was not affected by the gypsum except in one case when lime and gypsum at the rate of 1000 pounds per acre were applied together and this result is not conclusive.

The water-soluble potassium in the soil was increased by the application of gypsum and the greatest increase occurred when the gypsum was added at the rate of 1000 pounds per acre. The application of lime alone lowered slightly the amount of soluble potassium in the soil and its use with gypsum in most cases also reduced the action of gypsum alone upon the production of soluble potassium.

The results secured in a similar test with Canada field peas instead of alfalfa appear in table 14.

Observing the results in this table, it is found that the application of gypsum did not increase the crop yield except in one case and, in fact, in most instances a depression was noted.

The total nitrogen and total potassium in the crop was little influenced by the gypsum either alone or with lime, and in the case of the 500 and 1000-pound applications of gypsum alone decreases were noted. Lime alone did not increase the nitrogen content of the crop, but a slight increase in potassium occurred, which disappeared, however, when gypsum was added with the lime.

The application of gypsum had little or no effect on the nitrogen content of the soil, only in one instance showing any appreciable influence.

The water-soluble potassium in the soil was increased by gypsum alone, the greatest increase occurring with the largest application. Lime alone decreased the soluble potassium and when it was applied with gypsum there was an increase which was greater than that of gypsum alone, except where the largest amount of gypsum was used.

The results obtained on the tests with red clover are given in table 15. It may be seen that the crop yield was increased by the 100-pound application of gypsum but when lime was used with gypsum, decreases occurred. The nitrogen content of the crop was not affected by either the lime or the gypsum.

The potassium content of the crop was increased enormously by the gypsum in all amounts. Lime alone had no effect and the two materials together showed no increase over the effect of gypsum alone.

The application of gypsum had practically no effect on the nitrogen content of the soil and lime had only a slight effect. The production of water-soluble potassium in the soil was decreased by the application of gypsum, except where the largest amount was applied, when there was no effect. Lime alone decreased the soluble potassium and when used with gypsum there was no effect except with the 100-pound application, when a slight increase was noted.

The results secured with soybeans appear in table 16. Examining this table, it is found that gypsum applied in amounts larger than 100 pounds per acre decreased the crop yield. When lime was used a slight increase was noted and lime with 100 pounds of gypsum gave a still greater gain. With 1000 pounds of gypsum plus lime, however, a decrease over the effect of lime alone was noted.

TABLE 14

*Effects of gypsum on the solubility of potassium and on the total nitrogen content of the inoculated soil and crop of Canada field peas*

NUMBER	GYPSUM (CaSO <sub>4</sub> ) PER ACRE lbs. tons		LIMESTONE (CaCO <sub>3</sub> ) PER ACRE gm. gm.		CROP						SOIL					
					Crop yields		Total nitrogen		Total potassium		Total nitrogen		Water-soluble potassium			
					Per pot	Average	Per cent nitrogen	Average per cent	Per cent potassium	Average per cent	Nitrogen per 100 gm. of soil	Average	Per cent potassium	Average per cent	Pounds per acre	Average pounds per acre
											mgm.	mgm.				
1	Nil	Nil	10.35				3.16		1.70		92		0.0019		38.59	
2	Nil	Nil					3.16		1.54		92		0.0019		38.59	
3	Nil	Nil	8.70				2.94		1.35		92		0.0012		25.72	
4	Nil	Nil		9.52		2.96	3.05		1.41	1.50	92	92	0.0014	0.0016	28.70	32.90
5	Nil	3½	7.00				3.02		1.96		96		0.0014		28.70	
6	Nil	3½					3.02		1.83		92		0.0016		33.44	
7	Nil	3½	6.30				3.04		1.62		88		0.0012		25.72	
8	Nil	3½		6.65		3.02	3.02		1.60	1.71	88	91	0.0012	0.0013	25.72	28.40
9	100	Nil	8.25				3.04		1.44		100		0.0019		38.59	
10	100	Nil					3.06		1.31		95		0.0025		51.45	
11	100	Nil	9.75				3.00		1.54		89		0.0019		38.59	
12	100	Nil		9.00		2.98	3.02		1.55	1.46	86	92	0.0019	0.0020	38.59	41.78
13	500	Nil	11.90				2.84		1.36		98		0.0019		35.36	
14	500	Nil					2.80		1.35				0.0019		38.59	
15	500	Nil	10.50				2.94		1.06		97		0.0019		38.59	
16	500	Nil		11.20		2.84	2.85		1.06	1.21	97	97	0.0019	0.0019	38.59	37.78
17	1000	Nil	9.60				3.20		0.96		87		0.0025		51.44	
18	1000	Nil					1.12				87		0.0024		48.24	
19	1000	Nil	7.15				2.88		1.46		87		0.0027		54.67	
20	1000	Nil		8.37		2.88	2.99		1.44	1.24	87	87	0.0027	0.0026	54.67	52.25
21	100	3½	5.65						1.86		92		0.0035		70.75	
22	100	3½							1.86		93		0.0036		73.96	
23	100	3½	9.00				2.94		1.46		88		0.0018		37.31	
24	100	3½		7.32		2.94	2.94		1.35	1.63	89	90	0.0018	0.0027	37.31	54.83
25	500	3½	7.25				3.24		1.52		88		0.0041		83.61	
26	500	3½					3.24		1.59		92		0.0038		77.18	
27	500	3½	6.65				3.28		1.60		92		0.0028		57.88	
28	500	3½		6.95		3.28	3.26		1.54	1.56	89	90	0.0028	0.0034	57.88	69.14
29	1000	3½	9.85				2.90		1.55		89		0.0016		32.16	
30	1000	3½					2.90		1.46		89		0.0016		32.16	
31	1000	3½	7.65				2.76		1.57		85		0.0016		32.16	
32	1000	3½		8.75		2.72	2.82		1.39	1.49	86	87	0.0016	0.0016	32.16	32.16

The nitrogen content of the crop was enhanced by the gypsum when used with lime, however there was little increase over the effect of the lime alone. The total potassium in the crop was not affected by the gypsum but when lime was used with the gypsum a decrease occurred.

Gypsum alone had little effect on the nitrogen content of the soil, a slight increase occurring only in the case of the 1000-pound application. Used

TABLE 15

*Effects of gypsum on the solubility of potassium and on the total nitrogen content of the inoculated soil and crop of red clover*

NUMBER	GYPSUM (CaSO <sub>4</sub> ) PER ACRE	LIME- STONE (CaCO <sub>3</sub> ) PER ACRE	CROP						SOIL					
			Crop yields		Total nitrogen		Total potassium		Total nitrogen		Water-soluble potassium			
			Per pot	Average	Per cent nitrogen	Average per cent	Per cent potassium	Average per cent	Nitrogen per 100 gm. of soil	Average	Per cent potassium	Average per cent	Pounds per acre	Average pounds per acre
	lbs.	tons	gm.	gm.					mgm.	mgm.				
1	Nil	Nil	5.00		3.36		0.98		93		0.0035		70.75	
2	Nil	Nil			3.38		0.98		93		0.0022		45.02	
3	Nil	Nil	6.35		3.12		0.98		90		0.0022		45.02	
4	Nil	Nil		5.67	3.12	3.24	1.01	0.99	92	92	0.0035	0.0028	70.75	57.88
5	Nil	3 $\frac{1}{4}$	3.95		3.08		0.95		99		0.0016		32.16	
6	Nil	3 $\frac{1}{4}$			3.08		0.98		99		0.0022		45.02	
7	Nil	3 $\frac{1}{4}$	6.60		3.10		0.99		100		0.0016		32.16	
8	Nil	3 $\frac{1}{4}$		5.27	3.36	3.13	1.04	0.99	100	99	0.0028	0.0020	57.88	41.80
9	100	Nil	6.75		3.24		2.58		92		0.0019		39.87	
10	100	Nil			3.08		2.50		92		0.0016		32.16	
11	100	Nil	8.30		3.08		2.17		95		0.0019		38.59	
12	100	Nil		7.52	3.08	3.12	2.17	2.35	92	93	0.0035	0.0022	70.75	45.34
13	500	Nil	6.40		3.48		2.37				0.0025		51.45	
14	500	Nil			3.46		2.60		90		0.0032		64.32	
15	500	Nil	5.50		3.48		2.66		97		0.0025		51.45	
16	500	Nil		5.95	3.48	3.42	2.68	2.58	96	94	0.0025	0.0027	51.45	54.66
17	1000	Nil	4.45		3.46		2.31		99		0.0035		70.75	
18	1000	Nil			3.48		2.44		98		0.0025		51.45	
19	1000	Nil	6.05		3.52		2.41		98		0.0019		57.88	
20	1000	Nil		5.25	3.40	3.46	2.54	2.42	98	98	0.0035	0.0028	70.75	57.88
21	100	3 $\frac{1}{4}$	4.25		3.52		2.55		98		0.0035		70.75	
22	100	3 $\frac{1}{4}$			3.52		2.60		97		0.0032		64.32	
23	100	3 $\frac{1}{4}$	4.60		3.44		2.26		99		0.0025		51.45	
24	100	3 $\frac{1}{4}$		4.42	3.44	3.48	2.29	2.40	95	97	0.0032	0.0031	64.32	62.71
25	500	3 $\frac{1}{4}$	5.50		3.40		1.92		95		0.0019		38.59	
26	500	3 $\frac{1}{4}$			3.40		1.96		94		0.0022		45.02	
27	500	3 $\frac{1}{4}$	3.75		3.58		2.24		92		0.0032		64.32	
28	500	3 $\frac{1}{4}$		4.62	3.48	3.49	2.44	2.14	92	93	0.0029	0.0025	57.88	51.45
29	1000	3 $\frac{1}{4}$	2.80		3.36		2.12		97		0.0029		57.88	
30	1000	3 $\frac{1}{4}$			3.50		1.99		96		0.0029		57.88	
31	1000	3 $\frac{1}{4}$	4.80		3.36		2.15		99		0.0022		45.02	
32	1000	3 $\frac{1}{4}$		3.80	3.36	3.39	2.13	2.10	99	93	0.0022	0.0025	45.02	51.45

with lime no additional increase occurred. The soluble potassium in the soil was increased by the use of gypsum but lime caused a decrease. Lime used with the gypsum decreased the soluble potassium.

TABLE 16

*Effects of gypsum on the solubility of potassium and on the total nitrogen content of the soil and crop of soybeans*

NUMBER	GYPSUM (CaSO <sub>4</sub> ) PER ACRE	LIMESTONE (CaCO <sub>3</sub> ) PER ACRE	CROP						SOIL					
			Crop yields		Total nitrogen		Total potassium		Total nitrogen		Water-soluble potassium			
			Per pot	Average	Per cent nitrogen	Average per cent	Per cent potassium	Average per cent	Nitrogen per 100 gm. of soil.	Average	Per cent potassium	Average per cent	Pounds per acre	Average pounds per acre
			lbs.	tons	gm.	gm.			mgm.	mgm.				
1	Nil	Nil	9.25		1.32		1.27		105		0.0035		70.75	
2	Nil	Nil			1.48		1.31		105		0.0032		64.32	
3	Nil	Nil	11.00		1.60		1.28		107		0.0030		60.46	
4	Nil	Nil		10.12	1.60	1.50	1.17	1.26	106	106	0.0029	0.0031	57.80	63.33
5	Nil	3 $\frac{1}{4}$	11.50		1.54		1.27		107		0.0019		38.59	
6	Nil	3 $\frac{1}{4}$			1.54		1.21		104		0.0019		38.59	
7	Nil	3 $\frac{1}{4}$	11.25		2.00		1.43		107		0.0032		64.32	
8	Nil	3 $\frac{1}{4}$		11.37	2.04	1.78	1.39	1.32	103	105	0.0032	0.0025	64.32	51.45
9	100	Nil	11.25		1.16		1.10		101		0.0035		70.75	
10	100	Nil			1.24		1.18		107		0.0035		70.75	
11	100	Nil	9.25		2.24		1.33		114		0.0035		70.75	
12	100	Nil		10.25	2.32	1.74	1.27	1.22	107	107	0.0035	0.0035	70.75	70.75
13	500	Nil	7.00		1.18		1.27		107		0.0035		70.75	
14	500	Nil			1.34		1.27		112		0.0038		77.18	
15	500	Nil	10.00		2.96		1.18		112		0.0038		77.18	
16	500	Nil		8.50	2.76	2.06	1.14	1.20	112	111		0.0037		77.37
17	1000	Nil	8.50		3.58		1.28		109					
18	1000	Nil			3.48		1.30		109					
19	1000	Nil	9.25		1.56		1.09		108					
20	1000	Nil		8.87	1.52	2.53	1.18	1.21	107	108				
21	100	3 $\frac{1}{4}$	11.5				1.17		107					
22	100	3 $\frac{1}{4}$					1.15		112					
23	100	3 $\frac{1}{4}$	13.5		1.58		0.96		107					
24	100	31		12.50	1.58	1.58	1.06	1.08	107	108				
25	500	3 $\frac{1}{4}$	12.0		1.60		1.02		107		0.0016		32.16	
26	500	3 $\frac{1}{4}$			1.76		0.96		113		0.0016		32.16	
27	500	3 $\frac{1}{4}$	10.0		1.76		1.12		113		0.0029		57.80	
28	500	3 $\frac{1}{4}$		11.00	1.80	1.73	1.18	1.07	107	110	0.0029	0.0022	57.80	44.98
29	1000	3 $\frac{1}{4}$	10.25		2.04		1.28		110		0.0016		32.16	
30	1000	3 $\frac{1}{4}$			2.02		1.02		110		0.0016		32.16	
31	1000	3 $\frac{1}{4}$	9.75		1.78		1.12		110		0.0022		45.02	
32	1000	3 $\frac{1}{4}$		10.00	2.04	1.97	1.18	1.15	109	110	0.0022	0.0019	45.02	38.59

## DISCUSSION OF RESULTS

A study of the results of the bacterial tests, as summarized in tables 17, 18 and 19, reveals the fact that gypsum applied in various amounts had little effect on ammonification and nitrification in the particular soil, showing in most cases a slight depression in these processes, but azofication was increased, especially when used with lime.

TABLE 17  
*Summary of ammonification results*

NUMBER	POUNDS OF $\text{CaSO}_4$ AND TONS OF $\text{CaCO}_3$ PER ACRE	AVERAGE AMMONIA NITROGEN IN 100 GM. OF AIR-DRY SOIL					
		Sam-pling 1	Sam-pling 2	Sam-pling 3	Sam-pling 4	Sam-pling 5	Sam-pling 6
		mgm.	mgm.	mgm.	mgm.	mgm.	mgm.
1	None .....	130.80	96.60	133.40	126.26	134.54	134.40
2	$3\frac{1}{2}$ tons $\text{CaCO}_3$ .....	150.35	138.38	162.85	151.80	203.07	211.20
3	100 pounds $\text{CaSO}_4$ .....	124.95	89.43	130.85	120.65	142.48	120.77
4	500 pounds $\text{CaSO}_4$ .....	139.75	102.35	128.25	124.31	143.37	133.92
5	1000 pounds $\text{CaSO}_4$ .....	62.90	113.63	135.45	114.26	136.58	123.01
6	100 pounds $\text{CaSO}_4$ + $3\frac{1}{2}$ tons $\text{CaCO}_3$ ..	71.85	154.28	141.60	129.04	209.44	195.70
7	500 pounds $\text{CaSO}_4$ + $3\frac{1}{2}$ tons $\text{CaCO}_3$ ..	72.70	115.77	148.35	168.14	207.08	205.67
8	1000 pounds $\text{CaSO}_4$ + $3\frac{1}{2}$ tons $\text{CaCO}_3$ ..	66.6	135.85	158.30	155.93	172.51	193.99

TABLE 18  
*Summary of nitrification results*

NUMBER	POUNDS OF $\text{CaSO}_4$ AND TONS OF $\text{CaCO}_3$ PER ACRE	AVERAGE NITRATE NITROGEN IN 100 GM. OF AIR-DRY SOIL					
		Sam-pling 1	Sam-pling 2	Sam-pling 3	Sam-pling 4	Sam-pling 5	Sam-pling 6
		mgm.	mgm.	mgm.	mgm.	mgm.	mgm.
1	None .....	10.50	13.90	18.20	14.67	12.30	9.40
2	$3\frac{1}{2}$ tons $\text{CaCO}_3$ .....	16.56	15.70	24.50	21.87	17.50	15.30
3	100 pounds $\text{CaSO}_4$ .....	8.90	12.20	20.65	12.27	9.60	10.90
4	500 pounds $\text{CaSO}_4$ .....	9.30	13.30	14.40	12.37	7.20	8.55
5	1000 pounds $\text{CaSO}_4$ .....	10.44	16.40	15.30	9.05	10.40	8.25
6	100 pounds $\text{CaSO}_4$ + $3\frac{1}{2}$ tons $\text{CaCO}_3$ ..	17.30	17.70	17.00	12.97	15.45	14.15
7	500 pounds $\text{CaSO}_4$ + $3\frac{1}{2}$ tons $\text{CaCO}_3$ ..	20.65	17.30	16.20	13.77	16.00	12.60
8	1000 pounds $\text{CaSO}_4$ + $3\frac{1}{2}$ tons $\text{CaCO}_3$ ..	20.60	12.25	15.55	17.96	14.70	13.60

The ammonifying power of the soil was depressed, except in a few cases, by the different amounts of gypsum alone, the particular amount exerting the greatest depression varying at the different samplings. The results are extremely irregular and probably definite conclusions should not be drawn along this line. The application of lime alone greatly stimulated this process but the use of gypsum with lime in general gave a smaller effect than the lime alone. The two materials, however, brought about a distinct increase

over the ammonification in the untreated soil. Whatever the cause of the injurious effect of gypsum on ammonification it is evidently partly overcome by the presence of the lime. This would seem to indicate that the injury was due to the acidity developed.

The nitrifying power of the soil also was depressed by the gypsum in practically all cases, and in general the larger amounts brought about the greater decreases. Lime alone stimulated the process of nitrification considerably and the application of gypsum and lime together also gave an increase over the nitrification in the check soil, but after the second sampling the stimulation was never as marked as it was when lime was used alone. At the first two samplings there were indications of slight increases from the two materials together over lime alone, but the results are not very definite. Again, the lime seems to overcome the injurious effect of gypsum, in part at least, but even with lime present the gypsum does not seem to exert any beneficial effect.

TABLE 19  
Summary of azofication results

NUMBER	POUNDS OF $\text{CaSO}_4$ AND TONS OF $\text{CaCO}_3$ PER ACRE	AVERAGE NITROGEN FIXED IN 100 GM. OF AIR-DRY SOIL					
		Sam- pling 1	Sam- pling 2	Sam- pling 3	Sam- pling 4	Sam- pling 5	Sam- pling 6
		mgm.	mgm.	mgm.	mgm.	mgm.	mgm.
1	None .....	1.50	1.20	2.75	2.90	2.00	3.00
2	$3\frac{1}{2}$ tons $\text{CaCO}_3$ .....	4.50	1.70	2.25	5.60	4.50	5.00
3	100 pounds $\text{CaSO}_4$ .....	6.25	4.50	4.75	9.60	1.50	3.00
4	500 pounds $\text{CaSO}_4$ .....	4.00	4.80	1.75	2.60	2.00	2.00
5	1000 pounds $\text{CaSO}_4$ .....	4.12	6.30	2.25	2.65	3.50	1.00
6	100 pounds $\text{CaSO}_4$ + $3\frac{1}{2}$ tons $\text{CaCO}_3$ ..	10.75	8.30	3.50	6.35	6.50	14.00
7	500 pounds $\text{CaSO}_4$ + $3\frac{1}{2}$ tons $\text{CaCO}_3$ ..	10.55	4.30	3.37	6.60	8.50	6.50
8	1000 pounds $\text{CaSO}_4$ + $3\frac{1}{2}$ tons $\text{CaCO}_3$ ..	12.25	2.80	9.75	3.35	5.50	5.00

With few exceptions, the azofying power of the soil was increased by the application of the smallest amount of gypsum alone at the earlier samplings. The larger amounts of gypsum, however, gave definite increases in azofication only at the first two samplings and at the later dates little effect was noted.

Lime alone produced a stimulation in this process but when gypsum was used with lime the increases were much more pronounced. In the case of this process, the gypsum seems to have no depressing effect as on ammonification and nitrification, and hence it would seem that there can be little increase in acidity inasmuch as azofication is sensitive to acidity. Evidently sulfate benefits this process while it has a different effect on the other processes. It may be that the food requirements of the particular bacteria are very different.

The amounts of nitrogen fixed by *B. radicola* were much greater in the soil than in the solution. Gypsum generally increased the process, the greatest increase occurring with the largest application of gypsum. The fact that

a greater amount of nitrogen was fixed in the soil than in the solution is very probably due to the difference between the soil and the solution as a medium for the best bacterial activities.

The crop yields are so extremely variable that conclusions are difficult. In general, however, it seems that gypsum alone had little effect either on wheat or on the various legumes. In a few cases increases were noted and in others slight decreases were evidenced, but in general the differences secured were not very definite. Lime and gypsum together likewise exerted little effect on the crops and in general gypsum used with lime did not increase the yield of legumes over lime alone.

The acidity of the soil was increased by the applications of gypsum alone, the larger amounts producing the greatest increase. When applied with lime, the gypsum brought almost a slight acid condition in the soil, whereas the

TABLE 20  
*Production of water-soluble potassium in the soil*

NUMBER	POUNDS OF $\text{CaSO}_4$ AND TONS OF $\text{CaCO}_3$ PER ACRE	AVERAGE WATER-SOLUBLE POTASSIUM PER ACRE IN FALLOW SOIL	AVERAGE WATER-SOLUBLE POTASSIUM PER ACRE IN INOCULATED SOILS GROWING CROPS OF			
			Alfalfa	Canada field peas	Red clover	Soy-beans
		lbs.	lbs.	lbs.	lbs.	lbs.
1	None.....	74	45	32.90	57.88	63.33
2	$3\frac{1}{2}$ tons $\text{CaCO}_3$ .....	152	36.96	28.40	41.80	51.45
3	100 pounds $\text{CaSO}_4$ .....	72	57.86	41.78	45.34	70.75
4	500 pounds $\text{CaSO}_4$ .....	40	49.80	37.78	54.66	77.37
5	1000 pounds $\text{CaSO}_4$ .....	95	65.92	52.25	57.88	
6	100 pounds $\text{CaSO}_4$ + $3\frac{1}{2}$ tons $\text{CaCO}_3$ .....	198	57.88	54.83	62.71	
7	500 pounds $\text{CaSO}_4$ + $3\frac{1}{2}$ tons $\text{CaCO}_3$ .....	193	45.00	69.14	51.45	44.98
8	1000 pounds $\text{CaSO}_4$ + $3\frac{1}{2}$ tons $\text{CaCO}_3$ .....	183	44.98	32.16	51.45	38.59

limed soil gave a neutral reaction. It would seem evident from these results that gypsum does make the soil acid and when used lime should be applied in sufficient amounts so that no injurious effect can occur.

The production of water-soluble potassium in the fallow soil was apparently not affected by the use of smaller amounts of gypsum as shown in table 20, but there was a slight increase when the largest application of gypsum was used. The application of lime alone and lime with gypsum increased considerably the production of soluble potassium in the fallow soil. Gypsum and lime together seemed to exert a greater effect than lime alone.

The production of soluble potassium in the soil where the leguminous crops were grown was increased in general by the applications of gypsum alone, the largest increase occurring with the largest addition of gypsum. The application of lime alone in all cases decreased the production of soluble potassium in the soils where legumes were grown but the use of gypsum with

lime sometimes brought about an increase. Again the results are somewhat variable but in general the smaller amounts of gypsum with lime proved beneficial, while the larger quantities showed little effect.

The utilization of soluble potassium in the crops would not explain the difference between these results and those secured on the fallow soil, and hence it would seem that the results are not sufficiently definite to warrant conclusions. The use of gypsum alone, however, apparently brings about distinct increases in the production of water-soluble potassium, and hence the beneficial effect of the material on crops may sometimes be due to this action.

#### SUMMARY

The results of these experiments lead to the following conclusions:

1. Ammonification was decreased by the application of gypsum alone, the greatest decrease occurring with the largest application of the material. Lime favored ammonification and lime with gypsum showed less effect in general than lime alone.
2. Nitrification was similarly depressed by gypsum alone but the use of gypsum and lime together increased this process.
3. One-hundred-pound applications of gypsum stimulated azofication and the larger amounts also stimulated the process in most cases, but to a less extent than the smaller amount alone increased azofication.
4. The amounts of nitrogen fixed by *B. radiculicola* were much greater in the soil than in the solution. Gypsum generally increased the process, the greatest increase occurring with the largest application of gypsum.
5. The 1000-pound application of gypsum increased the yield of red clover; other applications, however, did not have any effect either on the wheat or on the other leguminous crops. Lime alone increased the yield of wheat and clover considerably.
6. The application of gypsum increased the acidity of the soil, the larger amounts giving the greatest increase.
7. The nitrogen and the potassium content of the leguminous crops were not affected by gypsum, except in the case of red clover when an enormous increase in its potassium content was noted.
8. The nitrogen content of the soil was not markedly affected by gypsum.
9. A slight increase occurred in the production of soluble potassium in fallow soil by the addition of 1000 pounds of gypsum alone, but the other applications did not show any effect. Lime alone increased the soluble potassium considerably and lime with gypsum gave increases over the lime alone.
10. When leguminous crops were grown the production of soluble potassium was greatly increased by the use of gypsum alone, the greater increase occurring with the larger applications.

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## THE WATER-SUPPLYING POWER OF THE SOIL AS RELATED TO THE WILTING OF PLANTS<sup>1</sup>

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### ABSTRACT

This paper reports a preliminary study of soil moisture conditions considered from a dynamic point of view, as these are related to the wilting of ordinary plants. These conditions affect the plant directly through the water-supplying power of the soil, by which is meant the capacity of the soil to operate as a system or machine delivering water to the absorbing surfaces of the plant roots. Of course, this water-supplying power of the soil, for any given temperature, depends, in its turn, upon a complex of static conditions, such as the sizes and kinds of the solid particles in the soil, their arrangement (packing) and the water content per unit of soil volume. It is impossible, however, to derive from such of the static soil features as can be measured and expressed in quantitative terms, any single numerical expression for the water-supplying power of a given mass of soil. It has therefore seemed desirable to approach this whole problem from the dynamic side and to attempt to measure the water-supplying power directly, somewhat as the evaporating power of the air is measured by means of atmometers. If this might be accomplished it would make it possible to study the daily or seasonal march of soil water-supplying power in a manner similar to that in which the evaporating power of the air may now be studied.

The method employed in this preliminary study involved the use of small, porous-porcelain cones all having approximately the same area of surface in contact with the soil. At the time of a determination a weighed, dry cone is thrust into the soil and left for a suitable time period, after which it is removed, quickly brushed free from adhering soil, and reweighed. The amount of water absorbed from the soil by the instrument is taken as an approximate measure of the water-supplying power of the soil. This way of approaching the important problem of soil moisture is new, as is also the device employed, but the results thus far secured indicate considerable promise for future developments.

Plants of *Coleus blumei* and of wheat (*Triticum sativum*) were grown in twelve different soils, including a heavy loam, a sand and a very pure humus,

<sup>1</sup> Botanical contributions from the Johns Hopkins University, no. 64.

together with various mixtures of loam and sand, loam and humus, and sand and humus. When the plants were in healthy condition the watering of the cultures was discontinued and wilting was allowed to occur. At or about the critical stage of "permanent wilting" the water-supplying power of the soil about the roots was determined by the new method. It was found that this value was from 0.04 to 0.11 gm. (average, 0.085) for 2 hours and for the porous porcelain cones used. The average was the same for *Coleus* as for wheat. In the case of *Coleus* the variations of this value from culture to culture were not at all related to the kind of soil or to its water-holding power; sand, loam and humus all agreed, when the plants were about the critical point, in giving a value of 0.09. In the case of wheat there is some suggestion that the soils of higher water-holding power gave very slightly higher values than did the others; for sand, loam and humus the corresponding values were 0.04, 0.09 and 0.10, respectively. But each test is based on only a single determination, so that this is but a suggestion. In any event, the index of water-supplying power may be regarded as practically the same for all twelve soils. It will probably be found to differ markedly for different kinds of plants (although it seems to be about the same in the cases of *Coleus* and wheat), for the same kind of plant grown under different moisture conditions, and for plants of the same kind grown under the same moisture conditions but brought to permanent wilting under different moisture conditions. The water-supplying power of all these soils, at the beginning of permanent wilting in these plants, was between 0.1 and 0.5 per cent of the water-supplying power just after a thorough watering of the pots, this latter value being the same for all the soils tested.

#### INTRODUCTION

The subterranean environmental moisture complex is directly influential upon plants through the water-supplying power of the soil, as has been emphasized by Livingston (6, 7, 12, 14). As far as plant water-relations are concerned, a soil is satisfactory for growth if it can supply water to the root system as rapidly as the latter can absorb it; the rate of external water supply at the absorbing surfaces does not become a limiting condition for growth until this rate falls below the rate of absorption demanded by the internal conditions of the plant. If, however, the soil is not capable of supplying moisture to the root system as rapidly as the latter can take it up, then the soil-moisture complex becomes a limiting condition for growth. As long as such a state of affairs prevails the growth of the plant, and other features of its activity, must be more or less markedly different from what they would be if water were more rapidly furnished to the roots.

The capacity of a given soil mass to deliver water to the root system of a plant rooted in it, might be relatively determined and defined as the maximum possible rate at which that particular soil mass (at the given instant)

is capable of delivering water to some standard water-absorbing surface. Relative measurements of the water-supplying powers of soils might be expressed in terms of the number of milligrams of water that could be delivered, in a unit of time, at a square centimeter of absorbing surface within the soil. Of course the actual absorbing surface used must be capable of removing the water as rapidly as it is delivered. It is obvious that the water-supplying power of a given body of soil at any given instant may vary from place to place within the soil (as at different depths, etc.), and that the numerical index of this soil condition must alter in value from time to time for any given region in the soil.

This dynamic point of view with regard to soil moisture is very different from the one heretofore generally taken in soil science and plant physiology. It promises to open the way to a definite advancement of our knowledge of the water relations of plants, in somewhat the same way as did the introduction of a corresponding point of view regarding the moisture conditions of the air (6, 8, 9). The experiments reported in this paper were planned as a working test of one method by which the water-supplying power of the soil may be studied directly, somewhat as the capacity of a machine to do the work of supplying water to the plant roots. A number of other methods have suggested themselves to one of the writers, from time to time during the period since 1904, and two or three of them have received some attention in the literature (6, 13, 14). The ones previously tested have shown themselves to be more suitable for refined laboratory work on artificially prepared masses of soil than they are for the field operations in regard to which adequate measurements of this dynamic soil condition are so greatly needed. The method resorted to in the present experiments is much simpler in its conception and much more satisfactory in use than any other that has thus far been suggested in the literature, and it has considerable promise for field work. This paper has been prepared partly to bring the dynamic point of view more into the prominence which it deserves in these connections, and partly with the hope that other interested workers may test and improve the method here introduced, the present writers being unable to carry the work farther in the immediate future.

As in the case of other conditions that directly affect the plant, the water-supplying power of the soil is dependent upon a complex of secondary conditions, including the static features generally discussed in connection with the subterranean water relations of plants. For any given small region in any given soil, at any given instant of time, the water-supplying power is clearly a function of a considerable number of measurable characters. Some of these static features are capable of definite description, but not all of them (12) can be readily characterized by single numerical indices, and the intrinsic difficulties here encountered are so great that there is no apparent hope for any indirect derivation of the index of the water-supplying power through the employment of secondary indices. If the kinds, sizes and arrangement

of the solid soil particles might be represented by a single numerical value and if the soil water content might be similarly stated, it would still be necessary to know just how to combine these two secondary values in order to obtain a true index of the water-supplying power. One of these two soil features, the water content, can be nicely, but somewhat laboriously, determined for any given region in a field soil by the method devised by Pulling (13). The work of obtaining information on this point for hundreds of soil samplings (at different times, for different depths, etc.) is at best not inviting, however. The other important static feature (or group of features) that would need evaluation for an indirect computation of a numerical value for the water-supplying power, is still farther beyond us at present; no satisfactory method for its estimation has been even suggested. The mechanical analysis throws no helpful light on the subject. Determination of the water-holding power or of the water equivalent would require that this static feature should be measured without disturbing the arrangement (packing) of the soil particles, and this is not readily feasible at present. On the whole, the indirect determination of the water-supplying power (the only soil feature that directly influences plants, as far as their water relation is concerned) is quite hopelessly out of the question at present, even if it were desirable to approach the problem in such a round-about manner.

The calculation of a numerical index for an immediately effective environmental condition, from values representing conditions that are not immediately effective upon the plant (conditions that influence the plant only through their determination of the effective condition, which, in turn, influences the plant), is logically undesirable in every case. It is far more satisfactory to measure the intensity and duration of the effective condition directly, whenever this can be done. Thus, the evaporating power of the air may be directly measured by atmometric methods, without dealing with measurements of air temperature, air moisture and air movement, and without attempting the very difficult operation of integrating these three data to give an index of evaporating power. From such considerations as those suggested above it becomes increasingly clear that feasible ways for making direct measurements of the water-supplying power of the soil are among the greatest present desiderata in soil science, plant physiology, ecology, etc. This dynamic condition cannot be evaluated by indirect means and it would be undesirable to evaluate it indirectly even if that were possible and feasible.

#### POROUS-PORCELAIN SOIL-POINTS FOR THE QUANTITATIVE DETERMINATION OF THE WATER-SUPPLYING POWER OF THE SOIL

The new method for directly obtaining a single numerical index of the dynamic soil feature here emphasized is based on the fact that dry, unglazed, porous porcelain exhibits a remarkable capillary attraction for water, so that this material may be made to present a good water-absorbing surface to the

soil. Our method consists, in short, in placing an "artificial root," made of dry porous porcelain, in the soil and determining how much water is absorbed in a given time period. It is desirable that determinations be made as easily and as rapidly as possible, and the soil must not be disturbed more than is absolutely necessary in making a determination. Also, determinations of the water-supplying power of the soil need to be made for various depths as well as for different positions in a horizontal plane.

With these ideas in mind, the "artificial roots" were planned as hollow cylinders of porous porcelain (similar to the material out of which porous-porcelain atmometer cups, etc., are made) having one end open while the other is closed and tapers to a conical point. A portion of the surface nearest to the pointed end is water-proofed, as is also the entire cylindrical surface and a ring of the conical surface adjacent to its junction with the cylindrical part. There is left, for water absorption, a conical surface that may be readily brought into close contact with the soil at any depth. Both the water-proofed and the absorbing surfaces are of such nature that clinging soil particles may be easily removed by brushing, and the porcelain is sufficiently resistant so that there is practically no danger of any of this material being lost. The instrument is first dried and weighed in the dry condition, it is then inserted in the soil at the place to be investigated, and left for a suitable time period, after which it is removed, brushed and reweighed. The increase in weight is a measure of the amount of water absorbed from the soil. The instrument can be used repeatedly, but of course requires to be dried before each application. These "artificial roots" have been termed *soil-points* for the present discussion; a better term may be evolved later if the instrument becomes generally used.

It is seen at once that this method involves the use of a number of soil-points in the same study and that it is desirable that they should be as nearly alike in their water-absorbing power as is possible. This means that the water-absorbing part should be of the same sort of material and that this surface should have the same area and form in all instruments. It is possible that different kinds of material and different sizes and forms of water-absorbing surface may be used interchangeably if suitable coefficients of correction have been obtained by preliminary standardization, but this possibility has not yet been studied.

The soil-points thus far available are 13.5 cm. long, the cylindrical portion being 8 cm. long and 2.5 cm. in outside diameter. The wall is about 3 mm. thick. The conical portion is 5.5 cm. long and tapers from a point to an outside diameter of 2.5 cm. They are water-proofed from the tip for a distance of about 1 cm. and the absorbing portion extends from the margin of this water-proofed area to the lower margin of the water-proofed upper portion, the conical absorbing surface being 2. cm. high, 1.1 cm. in diameter at one end and 2 cm. in diameter at the other. The absorbing surface therefore has an area of proximately of 10 sq. cm.

To insert the points in pots of soil without pebbles or other obstacles it is necessary simply to plunge them in from the free soil surface, after the manner of setting a stake in soft soil. They must be inserted far enough so that all of the absorbing surface shall be in contact with the soil; otherwise this surface may be placed at any desired depth. When the depth of the soil region to be studied is so great that the whole porcelain piece comes to lie below the free soil surface, a special device for placing and recovering the soil-point is necessary, but this exigency was not encountered in these preliminary tests and ways of meeting it need not be discussed here.

If the soil to be studied offers obstacles to the easy penetration of the soil-points it is desirable to make an opening first, of the proper size to receive the instrument. Perhaps a metal replica of the soil-point may be best suited for this. In our work we have made the preliminary opening in the soil by means of one of the soil-points that had been completely water-proofed, so as to have no absorbing surface. For some of the harder soils a cylindrical section was first removed with a cork-borer. Our soils contained no pebbles.

In thrusting the soil-point into the soil the conical portion acts, as it moves downward, to displace the soil laterally and to compress it to some extent. This disturbance can not be avoided in using any method of the sort here considered, but the compression produced should be similar for all tests. For this reason, and for others, it may be ignored for the present. It may be added that this artificial compression of the soil near the surface that is to be tested is not unlike what occurs as a root elongates and forces its tip into new regions of the soil. The compression should act generally to render the readings of the instrument a little higher than would be the case if the soil were not compressed.

When the absorbing surface of the soil-point has reached the desired depth it is left in position for the standard time period, care being taken, of course, not to tilt the instrument laterally and thus break the capillary continuity between the soil and any part of the conical surface. We have found that two hours is satisfactory as a standard time of exposure in cases where the water content of the soil tested does not approach the content that satisfies the water-holding power of the soil. When the soil is very wet a shorter time should be employed.

At the end of the period of exposure the soil-point is removed from the soil and any clinging soil particles are brushed off, after which it is placed in a weighed celluloid cylinder of suitable size, with sliding cap. The final weighing should be accomplished without removing the instrument from its case. After this weighing the porcelain piece is removed from its case and dried at 102°-105°C., for 24 hours or longer. It is then taken from the oven and cooled in a desiccator, being finally returned to its case for transmission to the place where the next exposure is to be made. It is well to store the soil-points generally in a desiccator, although the celluloid cases are practically sealed against water absorption.

## EXPERIMENTATION AND RESULTS

In order to be able to test soils of many different natures, we employed a fine glass sand, a somewhat clayey loam and a humus containing very little mineral matter, together with mixtures of sand and loam, sand and humus, and loam and humus. Three mixtures were used for each combination, the two components having the volumetric proportions of 1:3, 1:1 and 3:1. There were thus twelve different soils in the series. The water-holding power of each soil was determined by the Hilgard method (1-cm. column), and it was found that the twelve soils might be arranged so as to form a rather even series on the basis of this soil feature. They were numbered in the order of their values for water-holding power, and their numbers, together with the proportions of the three components in each case, and the corresponding water-holding-power values, are shown in table 1. The water-holding capacity is shown as percentage of the dry volume and also as percentage of the dry weight. It is seen that soil 1 is sand (with a volumetric water-holding power of 40.7 per cent), no. 6 is loam (with a corresponding value of 57.7 per cent) and no. 12 is humus (with a value of 103.1 per cent).

Since the soil feature under consideration is to be dealt with as an indication of the relation between living plants and the moisture conditions of the soil about their roots, the new method here brought forward needs to be tested by comparison with similar measurements obtained by biological tests. If the reasoning of the preceding paragraphs is correct and if our proposed method for approximating the water-supplying power of the soil is satisfactory, as a means of describing a soil as the latter might affect plants, then it should follow that soils giving similar water-supplying powers ought to exert similar influences on the growing plants used as biological indicators. In order to test this proposition it is desirable to choose some critical condition of the plant in its response to soil moisture conditions and to determine the water-supplying powers of various different soils at times when all the plants are in the critical condition. As has been said, the soil-moisture complex of conditions does not directly influence the plant unless the water-supplying power of the soil has a value low enough so that this becomes a limiting condition, for the plant used and for the particular complex of aerial conditions, etc., that is operative in the test; in other words, unless the soil fails to supply moisture to the roots as rapidly as they would absorb it if it were adequately supplied. For any complex of non-soil-moisture conditions and for any set of internal conditions in the plant, an inadequate water-supplying power should become notably influential upon the organism through cessation of growth, progressive decrease in turgor, wilting, and dying of the tissues. The degree of incipient drying (of Livingston and Brown (11) ), is not so readily measured quantitatively as are some of the symptoms following the beginning of wilting. The beginning of wilting itself is a critical condition in the plant, but it is very difficult to be sure just when a given individual plant begins to wilt. This is

TABLE 1  
Results of experiments on the relation of the water-supplying power of the soil and the wilting of plants

		SOIL NUMBER											
		1	2	3	4	5	6	7	8	9	10	11	12
I. Volumetric portions of the three soil components	Sand.....	Only sand	3	1	1	3	.....	.....	1	.....	1	.....	.....
	Loam.....	.....	1	1	3	.....	Only loam	3	.....	1	.....	1	.....
	Humus.....	.....	.....	.....	.....	1	.....	1	1	1	3	3	Only humus
II. Water-holding power of soil (1-cm. column), per cent	Volumetric, on dry volume (A).....	40.7	43.0	45.8	50.7	55.7	57.7	67.5	71.1	79.5	81.4	86.5	103.1
	Gravimetric, on dry weight (a).....	28.9	32.8	37.0	43.6	43.9	56.8	70.3	64.4	90.6	91.0	114.0	140.5
III. Water-supplying power of drained saturated soil (10-cm. column) by soil-points. (Hundredths gram for 2-hour period, calculated from $\frac{1}{4}$ hour period.) (Average of averages, 1412)	First test.....	1448	1488	1224	1452	1776	1220	1440	1492	184	1468	1840	1196
	Second test.....	1540	1204	1316	1384	1292	1676	1308	1188	1328	1464	1224	1760
	Average (B).....	1494	1346	1270	1418	1534	1466	1374	1340	1276	1466	1482	1478

	1	2	3	4	5	6	7	8	9	10	11	12
IV. Water content of soil at critical wilting stage, <i>per cent</i> . (Critical content-residue)	Volumetric, on dry volume { Coleus Wheat.....											
V. Water-supplying power of soil at critical wilting stage, by soil-points. (Critical supplying-power-residue)	Hundredths { Coleus (Average, 8.5, Wheat (Average, 8.5)											

especially difficult when different kinds of plants, or differently grown individuals of the same kind, are to be compared. From a group of various kinds of plants that are beginning to suffer from progressive incipient drying it is almost impossible, as yet, to separate those in which wilting has actually begun from those that are not yet actually wilting and those that have already passed the beginning of wilting.

The only critical stage in progressive wilting that has thus far received much attention in the literature is the beginning of what has been called *permanent* wilting (1, 2, 3, 4). Permanent wilting has been defined as that stage of progressive wilting from which recovery fails to occur within a period of 24 hours, if the wilted plants are exposed to a practically water-saturated atmosphere (in darkness) during that period. To determine whether a given plant is permanently wilted, it is thus necessary to subject it to this 24-hour exposure to saturated air. But this procedure throws no light on the question as to whether the plant may not have already passed the *beginning* of permanent wilting. It may be much more seriously affected than it was at the beginning of this stage; indeed, a totally dead plant would fulfil the conditions of the saturated-air test, for it surely would not recover during the test period.

By considerable practice, however, it is possible for an observer to gain such facility of visual judgment as to be able to detect the beginning of permanent wilting with a fair degree of precision in a form with which he is familiar, without resorting to the saturated-air test, except as a check on his visual observation (1, 2, 3, 4, 5, 10, 15). We took advantage of this fact and adopted the beginning of permanent wilting as the most feasible critical condition to employ in the comparative tests. Healthy plants were grown in each of the twelve different soils already described, watering was discontinued when they had attained a good growth, and wilting was allowed to supervene and to progress until the permanent stage had just been attained. When permanent wilting had just begun the soil-point was applied to the soil and a measurement of the water-supplying power was obtained. If our determination of the beginning of permanent wilting were sufficiently precise, and if the soil-point method were satisfactory, all readings obtained from the soil-points should be approximately the same, without any reference to what kind of soil might be involved. Of course it is to be noted that the beginning of permanent wilting for any kind of plant occurs sooner when the organism is rooted in a soil with low water-holding power than when it is rooted in a soil with higher water-holding power, other conditions being alike in both cases, so that such tests as we are dealing with could not all be made on the same day. The plants in sand reached the critical stage of wilting several days before those in humus. The aerial conditions of the greenhouse room in which our cultures stood were nearly the same throughout the period of wilting, and all cultures of a series had been subjected to the same aerial conditions throughout their earlier period of growth. The plants were as nearly alike as

possible at the time watering was discontinued. Of course, there were chemical differences between our different soils, but this feature was purposely neglected in this study. There are many reasons for thinking that these chemical differences were practically without influence in determining the relation between the beginning of permanent wilting of the plants and the corresponding soil-point values.

The plants used in these tests were *Coleus blumei* and wheat (*Triticum sativum*). The *Coleus* plants had been propagated by cuttings and had grown for several weeks in 4-inch pots of the various soils described above. The wheat plants were grown from seed planted directly in the potted soils. Both varieties were well grown and apparently healthy when watering was discontinued. Wilting was allowed to progress until the critical stage corresponding to the beginning of Briggs and Shantz's permanent wilting had been attained, previous experience with similar plants and the saturated-air test having made it possible to detect the advent of this critical stage with considerable precision. The beginning of permanent wilting is more easily and definitely detected by visual observation in the case of *Coleus* than in that of wheat and it is probable that the *Coleus* plants were more nearly alike in their degree of wilting at the time of the soil tests than were the wheat plants; this matter will be referred to in connection with the results.

Twelve different soil-points were used. They had been subjected to several comparative tests in the same mass of soil and had given evidence of being about alike in their water-absorbing powers. As it finally developed, there were some differences in absorbing power, but these may be neglected in the present stage of our knowledge of this new method. These differences were probably no greater than the unavoidable differences between the surface contacts formed with the soil in different tests, or than the inaccuracies involved in determining just when the plants were at the critical stage of wilting that was desired.

At the time the tests were made, soil samples from the various pots were obtained, by means of a cork-borer—in the manner described by Shive and Livingston (15)—and the water content of each soil was determined, both on the volumetric and on the gravimetric basis. These water-content values (expressed as percentages of the dry volume or dry weight of the soil) correspond to the so-called "wilting coefficients" of Briggs and Shantz (12). This index may be called the *permanent-wilting content-residue*, or *critical content-residue*, of soil moisture; the values do *not* represent "non-available" water, since plants undoubtedly often continue to absorb moisture from the soil at a considerable rate long after permanent wilting has set in and even after they are dead. In table 1, section IV, are shown the critical content-residue values for the 24 different pots—12 different soils for each kind of plant. Besides showing these content-residues as represented on the usual, volumetric and gravimetric basis (C and c), table 1 (section IV) also presents each value in terms of the corresponding water-holding power of the soil (C/A

and c/a). This fractional or ratio index may be called the *critical content-residue fraction*, of soil moisture.

The values obtained by means of soil-points applied at the roots of the permanently wilted cultures, are shown in table 1, section V (D), as indexes of the water-supplying powers of the several soils at the time when permanent wilting had begun. These values are stated in terms of *hundredths of a gram* of water absorbed by each soil-point during an exposure period of 2 hours, but they are to be regarded merely as relative values. This index may be called the *critical supplying-power-residue*.

Finally, the values for the water-supplying power were obtained for each of the twelve soils when it had just been saturated and drained, in a 4-inch pot (10-cm.-column of soil). The pots were plunged in water for 2 hours, and then drained in a moist chamber for an hour, after which the soil-points were applied in the usual manner, excepting that the exposure period was shortened in this case to 30 minutes. Since the entrance of water into the porous porcelain of the soil-point acts directly to decrease the water-absorbing power of the material, and since there is comparatively little porous porcelain available in the soil-point here employed, it is clear that this instrument ought not to be used with a 2-hour exposure period when the water-supplying power of the soil is very high. This matter will require future investigation, and will need to be borne in mind as the soil-point method is improved; in the present case the readings were obtained for half-hour periods and each half-hour value was multiplied by 4, to give a derived 2-hour value. These latter are presented in table 1, section III. Two separate tests are represented in each case and the average value for each soil is shown in the lower line of this section of the table (B). This index may be termed the *greater water-supplying power* of the soil. Its value may be considered as approaching the *maximum* water-supplying power in each case, although the magnitude of the maximum for any soil mass is probably influenced by the surroundings, outside of the mass itself (for example, the kind of pot used, etc.). At any rate, whatever details further study may bring out, each of these *greater* supplying-power values may be taken to represent the condition of a pot of the corresponding soil when it has very recently been thoroughly watered, but after subterranean run-off has ceased.

Corresponding to what we have called the critical content-residue fraction, we have derived a *critical supplying-power-residue fraction* for each soil and plant, this being the ratio of the critical supplying-power-residue to the corresponding greater supplying-power, and the values of this index are shown in table 1, section V (D/B).

It may be remarked that the special terms just defined have been selected for their descriptive value rather than for simple brevity. After workers in this field have become generally familiar with these concepts the terms may be shortened and allowed to become less clearly descriptive. It is not our aim to promulgate any special terminology, although we venture to hope that

Greek words may not be introduced to replace our English ones; it is desirable that scientific terminology should be no more pedantic than is really necessary for precision. Perhaps the final outcome may be that letters may be employed in place of our somewhat cumbersome and obviously built-up expressions, just as has long been true in certain branches of physics.

From the data given in table 1 it is at once evident that the critical content-residue ( $C$  or  $c$ ) and the critical content-residue fraction ( $C/A$  or  $c/a$ ) both agree with the water-holding power ( $A$  or  $a$ ) in that they show a progressive increase in magnitude from a minimum index value for the sand to a maximum for the humus soil. As was to be expected, the higher the water-holding power of the soil, the higher is the critical content-residue. The volumetric water-holding power varies from 40.7 to 103.1 (or from unity to 2.5), and the corresponding critical content-residue varies from 2.3 to 48.8 (or from unity to 21.2) for *Coleus* and from 1.6 to 46.2 (or from unity to 28.9) for wheat. The critical content-residue (representing the soil moisture content at the time of the inception of the permanent wilting stage) is thus seen to increase more rapidly throughout the series of soils than does the water-holding power. The former is 21 or 29 times as large, while the latter is only 2.5 times as large, for the humus as for the sand. Roughly speaking, the critical content-residue increases in magnitude about ten times as rapidly, from sand to humus, as does the water-holding power. The volumetric content-residue fraction varies from 0.06 to 0.47 (from unity to 7.8) for *Coleus* and from 0.04 to 0.45 (from unity to 11.3) for wheat. Therefore, the value of this ratio increases more rapidly than does the index of water-holding power, but not as rapidly as does the index of the critical content-residue. Both the content-residue and the content-residue fraction are apparently determined by conditions that differ from soil to soil, so that neither one of them can be of any direct use in predicting the onset of permanent wilting. Nor can the water-holding power be used for this purpose, as has long been known, unless its index is somehow combined with the index of the critical content-residue, and these data show at least that the quotient of the latter divided by the former (the critical content-residue fraction) does not represent a way to accomplish this combination.

It is to be remembered that all these soils are to be considered as practically alike at the beginning of permanent wilting for either plant; by the biological test the entire twelve were alike in their moisture conditions as far as these affect wilting. It follows that any index or criterion of the soil-moisture complex that might be used for predicting the critical point of wilting ought therefore to show like values for all soils when the plants are all in the critical condition. Turning again to table 1 (section V, D), it is seen that this is exactly what the critical supplying-power-residue does show. This is best demonstrated for *Coleus*, for which the value of this index is exactly the same (9) for sand, loam and humus. Its variations, while apparently considerable (the minimum is 6 and the maximum is 10 in this case), bear no

suggestion of a relation to the progressively increasing series of values that have just been considered. In this regard the data for wheat are a little less definite in their indications, but it is more difficult to detect the beginning of permanent wilting in this plant than in *Coleus*, as has been said. From no. 6 to no. 12 in the soil series, the wheat data for the critical supplying-power-residue give the same indication as has just been pointed out for the entire series in the case of the other plant, but for the lower soil numbers this index value tends to be lower with lower water-holding power. As will be shown presently, however, the total variation (between 4 and 11) is really negligible in the present connection. Also, it seems probable that the wheat plants of soil 1 had progressed somewhat farther in the drying-out process than would be represented by the beginning of permanent wilting. It may be more nearly correct to consider the critical supplying-power-residue for soil 1 as 6 rather than 4, in which case the total variation would become less. (Making a similar arbitrary alteration in section IV of the table would bring the wheat data of that section into very close agreement with the *Coleus* data.)

The data of table 1, section III, demonstrate that the index of greater water-supplying power (B) has practically the same value for all soils, and that its variations exhibit no relation to the progressively increasing series of the water-holding-power values. Remembering that the soil series are arranged in the order of progressively increasing water-holding power, the truth of the last statement is clearly established by noting that the twelve soils, when arranged according to increasing values of this index, give the following series of soil numbers: 3, 9, 8, 2, 7, 4, 6, 10 (the last two are alike), 12, 11, 1, 5. There is surely no relation between the meanings of these figures and the order of their arrangement.

These average values of the greater water-supplying-power range from 1270 to 1534 and the average of averages is 1412. The maximum is 8.6 per cent greater than the mean and the minimum is 10 per cent smaller. The water contents corresponding to these supplying-power values, had they been determined, must have shown a progressive variation similar to that seen in the series of water-holding-power values (A).

When the index of the critical water-supplying-power-residue is divided by the corresponding index of the greater water-supplying power, giving the supplying-power-residue fraction (table 1, section V, D/B) we obtain another series of values that do not show any relation to the progressively increasing water-holding-power values, and that are to be considered as all practically alike. The last observation strengthens the conclusion that the critical water-supplying-power-residues (D) are to be taken as all alike, in spite of an apparently significant variation; they range only from a minimum of 0.5 to a maximum of 0.8 per cent of the corresponding greater supplying power, for *Coleus*, and from a minimum of 0.3 (or perhaps 0.4) to a maximum of 0.9 per cent for wheat. It is highly probable that our values for the greater

supplying power are considerably too low, since they are based on a 30-minute period, which is probably too long for this instrument in such soils. Some 15-minute determinations on sand, loam and humus gave an average value of 3.157 gm., from which the derived value for a 2-hour period is 25.256 gm., or 2525.6 hundredths of a gram, instead of the mean value above derived from all soils, 1412 hundredths. Taking these last indications into account, we may therefore conclude that the index of water-supplying power at the inception of permanent wilting has a value, for both *Coleus* and wheat, of between 0.1 and 0.5 per cent (approximately) of the greater water-supplying power.

#### GENERAL CONCLUSIONS

It appears that the critical stage of wilting dealt with in this paper (the beginning of Briggs and Shantz's permanent wilting) occurs when the water-supplying power of the soil (as the latter becomes progressively drier after watering has been discontinued) has reached a certain low value, and that the soil-point method as here applied is adequate to determine this value within a reasonable degree of precision. For these instruments this value lies between 4 and 11 hundredths of a gram absorbed in a 2-hour period of exposure, the mean being 8.5. Of course this critical value refers to the two plants we have preliminarily tested and to the particular complex of non-soil-moisture conditions of the environment (chemical conditions of the soil, atmometric and light conditions of the air, etc.) with which we have worked. The critical value of the water-supplying power of the soil here stated *must not be thought of as a constant* for all kinds of plants and for all degrees of evaporation, etc. It will not prove to be a constant of this sort any more truly than did the "wilting coefficient" of Briggs and Shantz, which varies in a regular and predictable way, for any given soil and plant, with the evaporating power of the air that obtains during the period of wilting (5). This critical water-supplying power of the soil *does not vary*, however, with the physical make-up of the soil; it is the same for sand, loam and humus and for various mixtures of these. Its relation to soil temperature has not been studied.

In order to present a clear picture of our present conception of the relations involved in the advent of permanent wilting, we may trace briefly the march of pertinent affairs during the drying-out process that leads to this critical stage of wilting. Consider a healthy plant (as of *Coleus*), rooted in a pot of any kind of soil in which it will grow healthily, and suppose temperature and evaporation conditions that are not severe enough to prevent good growth when the soil is wet. Now suppose that water is supplied to saturate the soil and that watering is thereafter discontinued. The water-supplying power of the soil at this time may be represented by an index value of about 2000, for our soil-points and for a 2-hour period of exposure. As time goes on, the soil becomes gradually drier and the index value for the water-supplying power decreases. The plant at first continues to obtain all the water that its

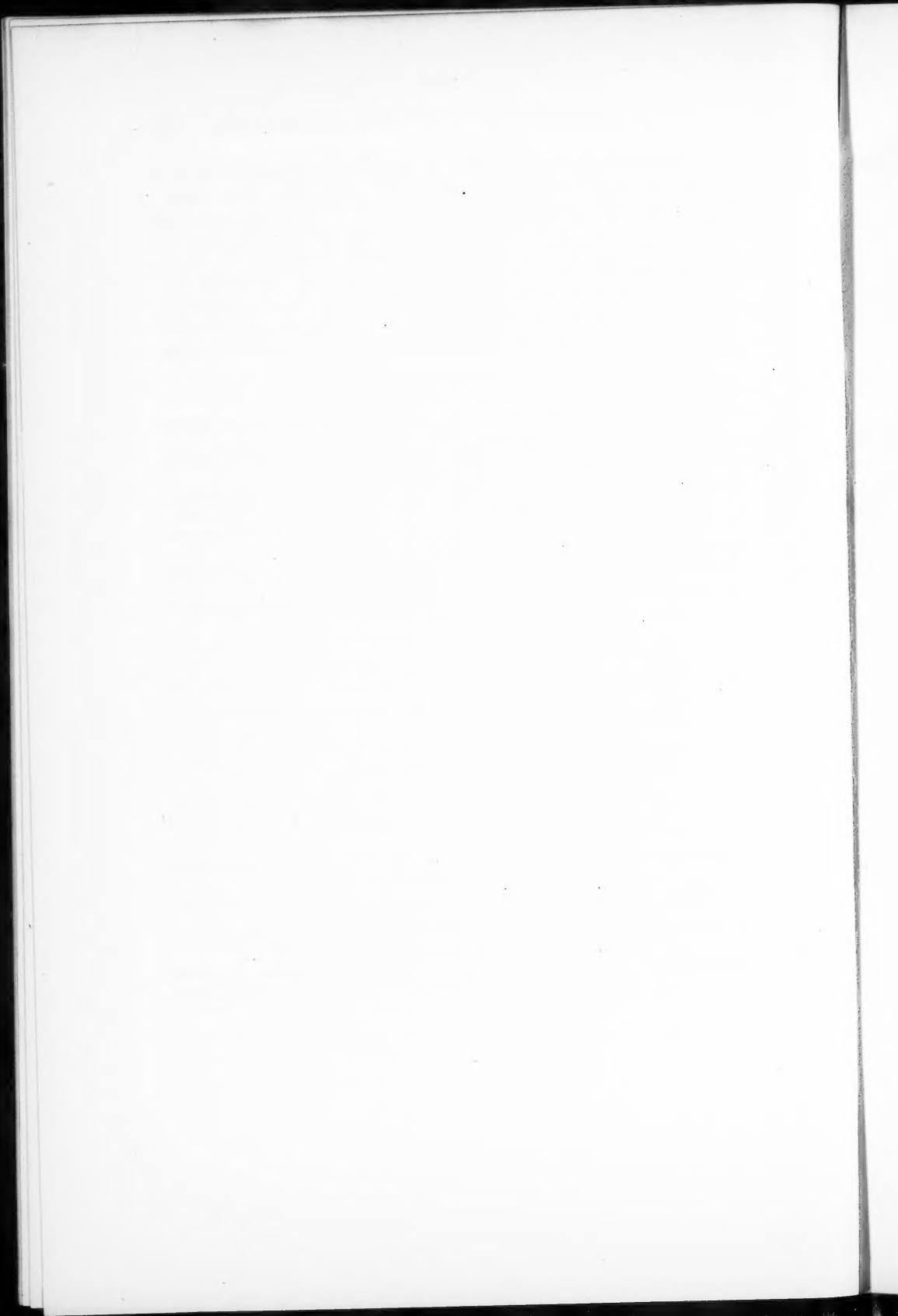
roots can absorb, and growth continues as previously. Sooner or later there comes a time, however, when the water-absorbing power of the plant is greater than the effective water-supplying power of the pot of soil. At this stage incipient drying becomes pronounced enough so that growth is retarded or checked. With the atmometric conditions remaining as they were, but with the water-supplying power of the soil continuing to diminish, cessation of growth is soon followed by some wilting. At first, the leaves appear wilted only for the driest part of the day, and recovery (perhaps even a renewal of growth) occurs for the night hours. As the index of soil-moisture-supplying power continues to decrease, there comes a time when the plant remains obviously wilted throughout the night. When this is true, either the evaporating power of the air is very high or the water-supplying power of the soil is very low, or both. Supposing the atmometric conditions to remain practically unchanged, however, with the same diurnal march as they have had previously, the various stages of progressive wilting each correspond to a certain value of the continually diminishing water-supplying power, and this value would be practically the same for all kinds of soils. Finally, the decreasing index of water-supplying power attains a value of about 8.5 (having started its decrease with a value of about 2000), for the general conditions of our experiments, and then permanent wilting begins. If the experiment is continued permanent wilting becomes progressively more pronounced as the moisture-supplying power goes on decreasing, and desiccation and the death of the plant eventually supervene.

Turning to the prospective value of the concept of water-supplying power and of instruments suitable for its direct measurement, it is clear that some sort of standardized instrument essentially similar to the soil-points used in our preliminary study will be a very great aid not only in physiological and ecological instrumentation but also in practical affairs, as in greenhouse culture, forest nursery work, and garden and agricultural operations. This instrument forms a much needed complement to the porous-cup atmometer, and when it becomes possible to employ the two together, along with soil and air thermometers, many of the present obstacles to progress in physiological ecology will disappear. For field work, the employment of such instrumentation as is suggested by our results will turn the attention of students away from the mechanical analysis of soils, the determination of their water contents, the measurement of rainfall, etc., and will bring into prominence the three directly effective conditional complexes (as far as water relations are concerned); namely, the evaporating power of the air, the evaporating power of radiation, and the water-supplying power of the soil. If these matters may receive the attention which they clearly deserve it may be possible to combine the atmometric index, the radio-atmometric index and the index of the water-supplying power of the soil, so as to obtain, at length, a valuable single index of the environmental-moisture complex as it affects plants.

In conclusion, we are very far from regarding the present contribution as a complete and satisfactory treatise on the problems with which we have dealt. The new apparatus and the methods of its use are as yet exceedingly crude, and time will be required for the accomplishment of many improvements that are as yet largely unthought of. Our paper is brought forward, in the present youthful stage of this sort of dynamic study, with the hope that others may appreciate the importance of pressing forward along the lines here suggested, to the end that physiology, physiological ecology, agriculture and forestry may become progressively more quantitative, more dynamic and more precise.

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## CARRIERS OF NITROGEN IN FERTILIZERS

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In the 5-year cereal rotation which has been conducted in duplicate on the Wooster and Strongsville farms of the Ohio Agricultural Experiment Station since 1894 at Wooster and since 1895 at Strongsville, plots 17, 21, 23, 24 and 30 have received equal quantities of phosphorus, potassium and nitrogen; the phosphorus being carried in acid phosphate on plots 17, 12, 23 and 24 and in acid phosphate and tankage on plot 30. The potassium has in all cases been carried in muriate of potash. The nitrogen has been carried in nitrate of soda on plot 17, in linseed oilmeal on plot 21, in dried blood on plot 23, in sulfate of ammonia on plot 24 and in tankage on plot 30. The same comparison has been repeated in the potato rotation at Wooster. Since 1900 half the land in the cereal rotation has been cross-dressed with ground limestone, applied at the rate of 2 tons per acre while preparing the land for corn. At Wooster the other half of the land has been left untreated, while at Strongsville it has been cross-dressed twice with raw phosphate rock, the total application amounting to  $1\frac{1}{2}$  tons per acre.

In these experiments every third plot is left without any fertilizer or manure, and the increase due to the treatment is computed by comparing each fertilized plot with the two unfertilized plots between which it lies, on the assumption that changes in the natural fertility of a field are more likely to be gradual than abrupt.

### THE CEREAL ROTATION AT WOOSTER

In tables 1 and 2 the results are shown in comparison both of the total yields of the crops and of the increase due to the treatments.

Table 2 shows that on this acid soil oats and wheat have given larger yields after nitrate of soda than after any other treatment, but corn and the hay crops have given the largest yields after tankage. The explanation seems to be that the nonacidulated phosphate in the tankage has been more favorable to the growth of clover—a fact very evident on inspection of the fields—than acid phosphate, and this improvement in the conditions for clover has been reflected in the timothy associated with it and in the corn immediately following.

Table 2 shows that on the limed land nitrate of soda has been the most effective carrier of nitrogen, with sulfate of ammonia a close second.

TABLE 1

*Comparison of carriers of nitrogen; Wooster, cereal rotation, unlimited land*

CROP	CARRIERS OF NITROGEN				
	Nitrate of soda	Linseed oilmeal	Dried blood	Sulfate of ammonia	Tankage
Average yield per acre*					
Corn (bushels) .....	46.77	46.68	47.42	45.79	48.43
Oats (bushels) .....	54.81	50.53	51.11	51.46	51.32
Wheat (bushels) .....	27.09	25.38	23.83	24.41	26.50
Clover (pounds) .....	2,372	2,022	1,923	1,986	2,718
Timothy (pounds) .....	2,969	2,772	2,730	2,740	3,491
Annual produce (pounds)† .....	3,970	3,719	3,655	3,676	4,058
Annual value .....	\$39.09	\$36.56	\$35.99	\$36.09	\$40.40
Average increase per acre					
Corn (bushels) .....	22.34	21.73	22.10	19.57	20.51
Oats (bushels) .....	24.78	20.94	21.74	21.73	18.84
Wheat (bushels) .....	15.34	13.54	12.07	12.39	14.51
Clover (pounds) .....	1,281	965	844	842	1,435
Timothy (pounds) .....	858	679	597	512	1,076
Annual produce† .....	1,702	1,462	1,390	1,360	1,565
Annual value .....	\$18.56	\$16.19	\$15.39	\$14.83	\$17.75

\* Average of 17 crops of corn, 15 of oats, 14 of wheat, 16 of clover and 12 of timothy.

† The "annual produce," as given in this and following tables, includes both grain and straw or stover, while the "annual value" is computed only on the grains and hay, rating corn at \$1.00 per bushel, oats at 75 cents, wheat at \$2.00 and hay at \$20.00 per ton. At these prices it is apparently immaterial, in these experiments, whether we use the total weight of produce, or the value of the grains and hay, as the common denominator for all the crops.

#### THE CEREAL ROTATION AT STRONGSVILLE

In table 3 is shown the outcome of this test at Strongsville for the 25 years of the experiment, 1905 to 1919, inclusive.

The uniformity shown in the total yields in this test is probably largely due to the apathy of this soil toward nitrogen fertilization.

In table 4 is shown the relative effect of nitrogen in the duplicate experiments at Wooster and Strongsville, in which the same crops are grown in succession, and plots of the same number receive the same treatment, in both kind and quantity of fertilizing materials.

Both nitrogen and potassium are comparatively ineffective on the Strongsville soil.

## THE POTATOES-WHEAT-CLOVER ROTATION AT WOOSTER

In the 3-year rotation of potatoes, wheat and clover at Wooster, plot 20 receives its nitrogen in nitrate of soda; plot 21 in linseed oilmeal; plot 23 in dried blood; plot 24 in sulfate of ammonia and plot 33 in tankage. Plot 33 was not included in this test until 1897, and therefore the results are given in table 5 for the 23 years, 1897 to 1919.

The application of lime in this rotation was begun in 1903 but was not completed until 1913. It is not apparent, however, that the liming has materially altered the relative effectiveness of the different nitrogen carriers.

In this experiment the natural fertility of the land is so high that there is less margin for increase from fertilizing than in the tests above described. Repeating the comparison made in table 4, we get the results for the potato rotation as shown in table 6; computed for the entire period of the experiment.

TABLE 2  
*Comparison of carriers of nitrogen; Wooster, cereal rotation, limed land*

CROP	CARRIERS OF NITROGEN				
	Nitrate of soda	Linseed oilmeal	Dried blood	Sulfate of ammonia	Tankage
Average yield per acre*					
Corn (bushels).....	54.64	53.98	54.06	55.35	51.42
Oats (bushels).....	55.63	54.57	53.71	54.64	51.19
Wheat (bushels).....	30.92	28.67	28.89	30.63	27.28
Clover (pounds).....	3,496	3,068	3,140	3,374	3,397
Timothy (pounds).....	4,596	4,039	4,057	4,365	4,381
Annual produce (pounds).....	4,538	4,215	4,250	4,392	4,280
Annual value.....	\$47.77	\$44.66	\$44.82	\$47.00	\$44.43
Average increase per acre					
Corn (bushels).....	24.85	22.98	22.50	23.03	17.81
Oats (bushels).....	21.47	19.25	18.24	18.75	14.32
Wheat (bushels).....	15.84	12.68	13.02	14.73	11.88
Clover (pounds).....	1,813	1,401	1,481	1,643	1,580
Timothy (pounds).....	1,569	1,045	1,051	1,224	1,154
Annual produce (pounds).....	2,160	1,700	1,737	1,868	1,592
Annual value.....	\$21.29	\$17.45	\$17.51	\$19.05	\$15.93

\* Average of 17 crops of corn, 15 of oats, 14 of wheat, 16 of clover and 12 of timothy.

TABLE 3

*Comparison of carriers of nitrogen; Strongsville, 25-year average yield and increase*

CROP	CARRIERS OF NITROGEN				
	Nitrate of soda	Linseed oilmeal	Dried blood	Sulfate of ammonia	Tankage
Average yield per acre					
Corn (bushels).....	41.52	38.66	39.91	37.94	41.81
Oats (bushels).....	52.38	53.00	53.54	54.10	51.29
Wheat (bushels).....	20.78	21.05	21.12	20.87	20.71
Clover (pounds).....	3,052	2,895	2,951	2,892	3,004
Timothy (pounds)*.....	2,180	2,261	2,277	2,203	2,096
Annual produce (pounds).....	3,414	3,430	3,474	3,413	3,378
Annual value.....	\$34.94	\$34.41	\$34.92	\$34.24	\$34.54
Average increase per acre					
Corn (bushels).....	12.85	10.15	11.25	9.60	15.54
Oats (bushels).....	14.52	12.72	12.95	14.07	14.71
Wheat (bushels).....	9.63	9.30	9.15	9.25	10.03
Clover (pounds).....	958	646	706	721	1,068
Timothy (pounds).....	395	372	396	366	454
Annual produce (pounds).....	1,040	922	917	918	1,119
Annual value.....	\$11.31	\$9.69	\$10.06	\$9.90	\$12.37

\* Timothy until 1914 and soybeans mown for hay since.

TABLE 4

*Relative effect of nitrogen at Wooster and Strongsville; 25-year average value of increase per acre*

PLOT	TREATMENT	ANNUAL VALUE OF INCREASE	
		Wooster	Strongsville
2	Acid phosphate.....	\$7.75	\$7.69
6	Acid phosphate and nitrate of soda.....	14.77	10.21
	Gain for nitrogen.....	\$7.02	\$2.52
8	Acid phosphate and muriate of potash.....	\$11.83	\$8.42
11	Acid phosphate, muriate of potash and nitrate of soda.....	18.14	11.24
	Gain for nitrogen.....	\$6.31	\$2.82

TABLE 5

*Comparison of carriers of nitrogen; Wooster, potato rotation, 23-year average yield and increase*

CROP	CARRIERS OF NITROGEN				
	Nitrate of soda	Linseed oilmeal	Dried blood	Sulfate of ammonia	Tankage
Average yield per acre					
Potatoes (bushels).....	169.13	160.45	160.62	161.98	158.63
Wheat (bushels).....	37.71	37.55	36.40	37.25	37.26
Clover (pounds).....	4,006	3,603	3,680	3,658	4,030
Annual value.....	\$94.87*	\$90.53	\$90.07	\$91.02	\$92.82
Average increase per acre					
Potatoes (bushels).....	39.90	36.76	37.50	39.73	31.65
Wheat (bushels).....	11.74	10.73	11.43	11.62	11.35
Clover (pounds).....	8.24	4.59	5.38	4.97	6.23
Annual value.....	\$23.87*	\$20.94	\$22.01	\$22.87	\$20.19

\* Rating potatoes at \$1.00 a bushel, wheat at \$2.00, and hay at \$20.00 a ton.

TABLE 6

*Effect of nitrogen in potatoes-wheat-clover rotation at Wooster, 25-year average value of increase per acre*

CROP	TREATMENT	ANNUAL VALUE OF INCREASE
2	Acid phosphate.....	\$7.73
6	Acid phosphate and nitrate of soda.....	12.50
	Gain for nitrogen.....	\$4.77
8	Acid phosphate and muriate of potash.....	\$17.73
11	Acid phosphate, muriate of potash and nitrate of soda.....	19.01
	Gain for nitrogen.....	\$1.28

## THE TOBACCO-WHEAT-CLOVER ROTATION AT GERMANTOWN

At the southwestern test farm of the Experiment Station, at Germantown, Montgomery County, a 3-year rotation of tobacco, wheat and clover has been in progress since 1903. In this experiment certain plots have received the following treatment:

Plot number	
8	Acid phosphate, muriate of potash, nitrate of soda
26	Same, with 1000 pounds of lime
16	Acid phosphate, muriate of potash, sulfate of ammonia
28	Same, with 1000 pounds of lime
18	Acid phosphate, muriate of potash, tankage
29	Same, with 1000 pounds of lime
22	Acid phosphate, nitrate of potash, nitrate of soda

The fertilizers have been calculated to carry 30 pounds of phosphorus, 75 pounds of potassium and 38 pounds of nitrogen in each case. On plots 18 and 29 all the nitrogen and the larger part of the phosphorus have been given in tankage, and on plot 22 all the potassium and the larger part of the nitrogen have been given in nitrate of potash. The fertilizers have all been applied to the tobacco crop, the wheat and clover following without further treatment.

The average yields obtained in this experiment during the 16 years, 1903-1918, are shown in table 7.

These results indicate a superiority of nitrate of soda over sulfate of ammonia on unlimed land, which disappears when the land is limed. The

TABLE 7

*Comparison of carriers of nitrogen; Germantown, average yields per acre*

CROP	CARRIERS OF NITROGEN			
	Nitrate of soda	Sulfate of ammonia	Tankage	Nitrate of potash
Unlimed land				
	<i>Plot 8</i>	<i>Plot 16</i>	<i>Plot 18</i>	<i>Plot 22</i>
Tobacco (pounds).....	1,227	1,095	960	1,131
Wheat (bushels).....	26.63	25.82	26.16	25.15
Clover (pounds).....	4,416	4,149	4,360	3,987
Annual values*.....	\$93.82	\$85.79	\$79.97	\$86.61
Limed land				
	<i>Plot 26</i>	<i>Plot 28</i>	<i>Plot 29</i>	
Tobacco (pounds).....	1,069	1,082	959	
Wheat (bushels).....	27.78	28.05	23.96	
Clover (pounds).....	4,139	4,193	4,054	
Annual values*.....	\$85.77	\$86.78	\$77.44	

\* Rating tobacco at 15 cents a pound; wheat at \$2.00 a bushel and hay at \$20.00 a ton.

tobacco has shown a marked preference for either of the other carriers of nitrogen over tankage, a preference evident throughout the growth of the crop, but the wheat and clover do not speak so positively on this point. It would seem that the tankage becomes available too slowly for such a short-season crop as tobacco.

The plots in this test are arranged in blocks of 10 plots, the first, fourth, seventh and tenth plot in each block being left continuously unfertilized, and the increase due to the fertilizers is calculated on the assumption that variations in the yields of consecutive unfertilized plots are due to progressive variations in the soil. By this method of calculation the increases due to the separate treatment are found as shown in table 8.

TABLE 8

*Comparison of carriers of nitrogen; Germantown, average increase per acre*

CROP	CARRIERS OF NITROGEN			
	Nitrate of soda	Sulfate of ammonia	Tankage	Nitrate of potash
Increase on unlimed land				
	Plot 8	Plot 16	Plot 18	Plot 22
Tobacco (pounds).....	656	623	506	600
Wheat (bushels).....	14.09	14.14	15.03	14.67
Clover (pounds).....	1,632	1,368	1,629	1,509
Annual value.....	\$47.63	\$45.14	\$40.75	\$44.81
Increase on limed land				
	Plot 26	Plot 28	Plot 29	
Tobacco (pounds).....	589	626	505	
Wheat (bushels).....	17.11	17.46	13.57	
Clover (pounds).....	1,907	1,934	1,798	
Annual value.....	\$47.21	\$49.39	\$40.29	

TABLE 9

*Comparison of carriers of nitrogen; annual values per acre at Wooster and Strongsville*

EXPERIMENT	CARRIERS OF NITROGEN				
	Nitrate of soda	Linseed oilmeal	Dried blood	Sulfate of ammonia	Tankage
Value of total produce					
Wooster cereal rotation, unlimed....	\$39.09	\$36.56	\$35.99	\$36.09	\$40.40
Wooster cereal rotation, limed.....	47.77	44.66	44.82	47.00	44.43
Wooster potato rotation.....	94.87	90.53	90.07	91.02	92.82
Strongsville cereal rotation.....	34.94	34.41	34.92	34.24	34.54
Average.....	\$54.17	\$51.29	\$51.45	\$52.09	\$53.05
Value of increase					
Wooster cereal rotation, unlimed....	\$18.56	\$16.19	\$15.39	\$14.83	\$17.75
Wooster cereal rotation, limed.....	21.29	17.45	17.51	19.05	15.93
Wooster potato rotation.....	23.87	20.94	22.01	22.87	20.19
Strongsville cereal rotation.....	11.31	9.69	10.06	9.90	12.37
Average.....	\$18.76	\$16.07	\$16.24	\$16.66	\$16.56

The wheat and clover show a larger increase over the unfertilized yields on the limed than on the unlimed land except on the tankage plot, where the wheat falls behind.

Unless the land is exceptionally uniform, the comparison of increases, calculated by the method employed in these experiments, is usually more reliable than that of entire produce.

#### SUMMARY

In table 9 the annual values found in the experiments at Wooster and Strongsville are collected for convenient comparison.

These results show that, with only two exceptions in the forty comparisons, nitrate of soda has produced the largest yield, and this outcome is supported by the results at Germantown, except on the limed land, where the yields from sulfate of ammonia slightly exceed those from nitrate of soda.

## INDEX

- Acidity of soils, versus sourness of soil, 211-212
- Albrecht, William Albert (paper), Symbiotic Nitrogen Fixation as Influenced by the Nitrogen in the Soil; see Nitrogen Fixation, etc., 275-327
- Algae, enumeration of species of, in New Jersey soils, 6-9
- Allison, F. E., Fellers, C. R., and (paper), The Protozoan Fauna of the Soils of New Jersey; see Protozoan Fauna of, etc., 1-26
- Ammonia, accumulation of—  
     as a measure for relative activity of heated and unheated soil infusions, 333-337  
     in the decomposition of green and cured clover in soil, 143-145
- Ammonification, effect of  $\text{CaSO}_4$  on, 446-452
- Ammonium nitrate, effect of, on availability of rock phosphate, 237, 241-245
- Ammonium sulfate in comparison with nitrate of soda as nitrogen carriers, 493-494
- Azofication, effect of  $\text{CaSO}_4$  on, 446-455
- Bacillus—  
     *coli*, reduction potentials of, 206-208  
     *mycoides*, reduction potentials of, 209  
     *radicicola*, effect of  $\text{CaSO}_4$  on, 452-455  
     *subtilis*, reduction potentials of, 205-206
- Bacteria, relation of protozoa to soil, 13-15
- Bacterial Activities, The Effect of Gypsum in Soils on (paper), Thakur Mahadeo Singh, 437-468  
     availability of plant-food, 456-462  
     bacteriological, 443-455  
     crop results, 455-456  
     discussion of results, 462-465  
     historical, 438-443  
     introduction, 437-438
- Bacterial cultures, reduction potentials of, 204-205, 208-209
- Bauer, F. C. (paper), The Effect of Leaching on the Availability of Rock Phosphate to Corn; see Phosphate Rock, the Effect of, etc., 235-251
- Bear, Firman E., and McClure, George M. (paper), Sampling Soil Plots, 65-75
- Bizzel, J. A., Lyon, T. L., and Wilson, B. D. (paper), The Formation of Nitrates in a Soil Following the Growth of Red Clover and of Timothy; see Nitrates, Formation of, etc., 53-64
- Blair, A. W., and Prince, A. L. (paper), The Lime Requirement of Soils, According to the Veitch Method, Compared with the Hydrogen-Ion Concentration of the Soil Extract, 253-259
- Lipman, J. G., and (paper)—Field Experiments on the Availability of Nitrogenous Fertilizers, 1908-1917; see Nitrogenous Fertilizers, etc., 371-392
- The Lime Factor in Permanent Soil Improvement—  
     I. Rotation without Legumes; see Lime Factor, etc., I, 83-90  
     II. Rotation with Legumes; see Lime Factor, etc., II, 91-114
- Buffer action in soils, 202, 264-265
- Calcium content of corn plant as affected by leaching when rock phosphate was used, acid phosphate,  $\text{NH}_4\text{NO}_3$  or  $\text{NaNO}_3$ , 241
- Carbon—  
     and nitrogen relationship, 146-147  
     percentage comparison with nitrogen in limed and unlimed soils, 87-88
- Carbon dioxide—  
     determination of, versus nitrate determinations in measuring rate of decomposition of organic matter in soil, 137  
     production from heated and unheated soil infusions, 338
- Carbonic acid, effect of, on solubility of rock phosphate, 235
- Cell sap, effect of moisture content of soil on the concentration of, in roots and tops of plants, 225-227

- Chlorides—  
 amount in soils, 44-45  
 Factors influencing the quantitative determination of, in soil, 41-51  
 Hirst and Greaves method of extraction of, 45-46  
 Mohz's method for determination of, 41-43, 46-47, 49-50  
 Volhard's method for determination of, 41-43, 46-47, 49-50  
 Chlorophyll, effect of, upon the reaction of plant juice, 362-364  
 Clover—  
 Green and Cured Tops, the Comparative Rate of Decomposition of, in Soil (paper), Albert L. Whiting and Warren R. Schoonover, 137-149  
 experimental work and results, 139-147  
 historical résumé, 138-139  
 methods of measuring rate of decomposition, 137-138  
 effect of growth of, on accumulation of nitrates, 59  
 Cropping, removal of soluble bases and acids by, 28-29  
 Dilatometer in studies of relationships between the concentration of the soil solution, cell sap and water that freezes in plant tissue, 217-219  
 Drainage, effect of, on vegetation, 212  
 Electrodes, various metals used for unattainable, 203-204  
 Elutriator, a New Soil (paper), Willard Gardner, 191-197  
 Fellers, C. R., and Allison, F. E. (paper), The Protozoan Fauna of the Soils of New Jersey; see Protozoan Fauna of, etc., 1-26.  
 Freezing-Point Lowering of Soils and Plants, Further Studies on the (paper), M. M. McCool and C. E. Millar, 217-233  
 effect of concentration of soil solution on the freezing-point lowerings of roots and tops of plants, 219-224  
 effect of moisture content of soils on the concentration of the cell sap in roots and tops of plants, 224-227  
 water that freezes in plant tissue under different temperatures, 217-219  
 Gardner, Willard (paper), A New Soil Elutriator, 191-197  
 Gillespie, Louis J. (paper)—  
 Colorimetric Determination of Hydrogen-Ion Concentration without Buffer Mixtures, with Especial Reference to Soils; see Hydrogen-Ion Concentration, etc., 115-136  
 Reduction Potentials of Bacterial Cultures and of Water-Logged Soils; see Reduction Potentials of, etc., 199-216  
 Greaves, J. E., Hirst, C. T., and (paper), Some Factors Influencing the Quantitative Determination of Chlorides in Soil, 41-51  
 Gypsum, effect of—  
 on acidity of soil, 456  
 on ammonification, 446-452  
 on azofication, 446-455  
 on *B. radiculicola*, 452-455  
 on nitrification, 446-452  
 on solubility of potassium and on the total nitrogen content of the inoculated soil and crop of—  
 alfalfa, 453-459  
 Canada field peas, 459-460  
 red clover, 460-461  
 soybeans, 461-462  
 Haas, A. R. C. (paper), Studies on the Reaction of Plant Juices; see Plant Juices, etc., 341-369  
 Heat, Concerning the Effect of, on the Reaction between Lime-Water and Acid Soils (paper), R. H. Robinson, 151-157  
 Hirst, C. T., and Greaves, J. E. (paper), Some Factors Influencing the Quantitative Determination of Chlorides in Soil, 41-51.  
 Howard, L. P. (paper), The Reaction of the Soil as Influenced by the Decomposition of Green Manure; see Reaction of the Soil, etc., 27-40  
 Hydrogen electrode, its behavior in solutions with minimal buffer action, 202  
 Hydrogen-Ion Concentration—  
 Colorimetric Determination of, with Buffer Mixture, with Especial Reference to Soils (paper), Louis J. Gillespie, 115-136  
 clear soil extracts by the use of colloidal iron, 132-134  
 experiment on which method is based, 118-127

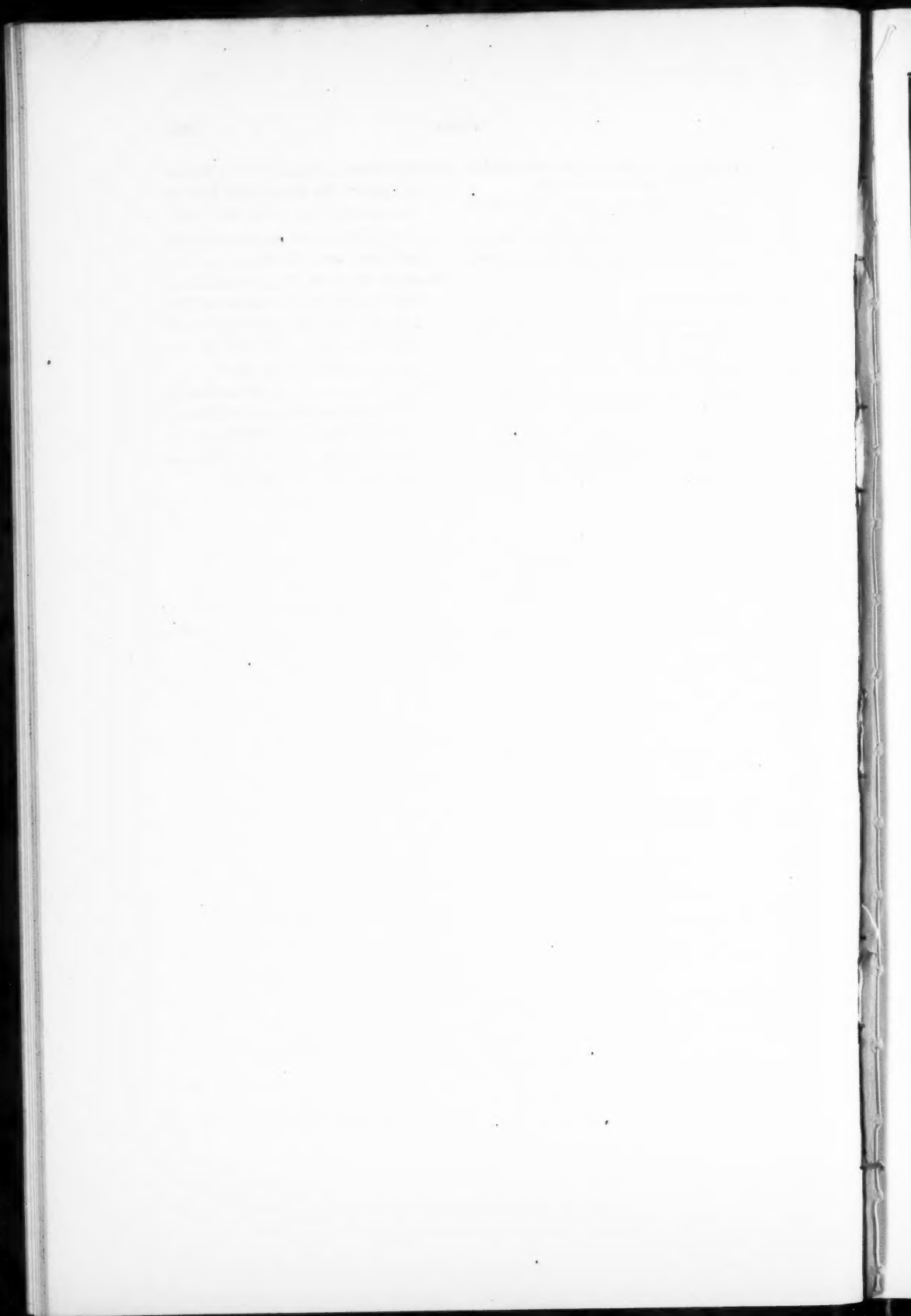
- preparation and use of color standards, 129-132
- preparation of indicator solution, 127-128
- principle of method, 116-118
- effect of moisture in soil on, 37-38
- effect of soil temperature on, 37-38
- effect of storage of soil on, 35-37
- in soil extracts, 35-37
- measurements in determining lime requirements, 256-258
- Measurements of Soils in Connection with Their "Lime Requirements" (paper), Jacob S. Joffe, 261-266
- of plant juices, 341-369
- relation of, to potato-scab control, 397-407
- Joffe, Jacob S. (paper), Hydrogen-Ion Concentration Measurements of Soils in Connection with Their "Lime Requirements," 261-266
- Jones method for lime-requirement determinations, 30-31
- Kearney, Thomas H. (paper), The Relative Absorption by Soil of Sodium Carbonate and Sodium Chloride, 267-273
- Koketsu, Riichiro, Livingston, Burton E., and (paper), The Water-Supplying Power of the Soil as Related to the Wilting of Plants; see Plants, the Wilting of, etc., 469-485
- Leaching—
  - effect of, on availability of rock phosphate, 237-241
  - removal of soluble bases and acids by, 28-29
- Lime—
  - amounts of, as determined by hydrogen-ion concentration measurements, 261-266
  - Factor in Permanent Soil Improvement, The—
    - I. Rotation without Legumes (paper), J. G. Lipman, and A. W. Blair, 83-90
    - effect of lime on nitrogen content of legumes, 83-84
    - experimental work, 84-90
    - II. Rotation with Legumes (paper), J. Lipman and A. W. Blair, 91-114
    - effect of lime—
      - on lime requirements of soils, 110-113
      - on nitrogen content of—
        - crops, 97, 101, 105, 110, 380-383
        - legumes, 83-84
        - soils, 110-113
      - on nitrogen recovered, 383-390
      - variable amounts of, on crop production, 97
    - magnesium lime, versus calcium, 91-114
  - Requirement of Soils According to the Veitch Method Compared with the Hydrogen-Ion Concentration of the Soil Extract (paper), A. W. Blair and A. L. Prince, 253-259
- Liming, effect of, on the actual and total acidities of plant juices, 346-356
- Lipman, J. G., and Blair, A. W. (paper)—
  - Field Experiments on the Availability of Nitrogenous Fertilizers, 1908-1917; see Nitrogenous Fertilizers, etc., 371-392
  - The Lime Factor in Permanent Soil Improvement—
    - I. Rotation without Legumes, see Lime Factor, etc., I, 83-90
    - II. Rotation with Legumes, see Lime Factor, etc., II, 91-114
- Livingston, Burton E., and Koketsu Riichiro (paper), The Water-Supplying Power of the Soil as Related to the Wilting of Plants; see Plants, the Wilting of, etc., 469-485
- Lyon, T. L., Bizzell, J. A., and Wilson, B. D. (paper), The Formation of Nitrates in a Soil Following the Growth of Red Clover and of Timothy; see Nitrates, Formation of, etc., 53-64
- MacIntire method for lime-requirement determinations, 30-31
- McClure, George M., Bear, Firman E., and (paper), Sampling Soil Plots, 65-75
- McCool, M. M., and Millar, C. E. (paper), Further Studies on the Freezing-Point Lowering of Soils and Plants; see Freezing-Point, etc., 217-233
- Manure, green, influencing soil reaction, 27-40
- Martin, William H. (paper), The Relation of Sulfur to Soil Acidity and to the Control of Potato Scab, 393-408

- Middleton, Howard E. (paper), The Moisture Equivalent in Relation to the Mechanical Analysis of Soils, 159-167
- Millar, C. E., McCool, M. M., and (paper), Further Studies on the Freezing-Point Lowering of Soils and Plants; see Freezing Point, etc., 217-233
- Moisture—  
 content of soil, effect of, on the concentration of the cell sap in roots and tops of plants, 224-227  
 effects of, on hydrogen-ion concentration of soils, 37-38  
 Equivalent in Relation to the Mechanical Analysis of Soils (paper), Howard E. Middleton, 159-167
- Muck soil, effect of aeration and other factors on the lime requirement of a, 77-81
- Neller, J. R. (paper), The Potential Biochemical Activity of the Spores of Soil Bacteria, 329-340
- Nitrate of soda in comparison with ammonium sulfate as nitrogen carriers, 493-494
- Nitrates—  
 accumulation of, in decomposition of green and cured clover in soil, 143-145  
 effect of growth of clover on accumulation of, 59  
 effect of growth of timothy on accumulation of, 59  
 effect of—  
   on soil and cowpeas grown in it, 296-309  
   on soil and soybeans grown in it, 289-296  
 Formation of, in a Soil Following the Growth of Red Clover and of Timothy (paper), T. L. Lyon, J. A. Bizzell, and B. D. Wilson, 53-64  
 experimental work, 55-63  
 literature review on nitrate accumulation, 53-55
- Nitrification, effect of  $\text{CaSO}_4$  on, 446-452
- Nitrogen—  
 and carbon-dioxide ratio, 137  
 Carriers of, in Fertilizers (paper), Charles E. Thorne, 487-494  
 changes in soil during the growth of legumes, 309-314  
 comparison of percentages of carbon and of, in limed and unlimed soils, 87-88  
 content of corn plant as affected by leaching when rock phosphate was used, acid phosphate,  $\text{NH}_4\text{NO}_3$  or  $\text{NaNO}_3$ , 241  
 depletion of, in limed soils, 88-90  
 effect of  $\text{CaSO}_4$  on fixation of, by *B. radicola*, 453-455  
 effect of lime on content of—  
   in legumes, 83-84  
   in crops, 97, 101, 105, 110  
 from mineral sources, versus organic nitrogen in crop production, 372-377  
 in drainage water—  
   after the soil had remained fallow for a month, 58-59  
   during growth of timothy and red clover, 57-58  
 influence of lime on content of, in soil, 110-113  
 removal of, from soil following the growth of timothy and red clover, 61-63
- Nitrogen (Symbiotic) Fixation—  
 as Influenced by the Nitrogen in the Soil (paper), William Albert Albrecht, 275-327  
 analytical methods, 287-288  
 discussion of crop series, 288-309  
 historical, 276-283  
 introduction, 275  
 nitrogen changes in soils during the growth of legumes, 309-314  
 plan of experiment, 284-287  
 by cowpeas on soils treated with nitrates, clover tops, or the two combined, 296-309  
 by soybeans on soils treated with nitrates, clover tops, or the two combined, 289-296  
 methods of measuring, 284
- Nitrogenous Fertilizer, Field Experiments on the Availability of (paper), J. G. Lipman and A. W. Blair, 371-392  
 income and outgo of nitrogen, 386-390  
 percentage of nitrogen in dry matter, 381-383  
 percentage of nitrogen recovered, 383-386  
 plan of experiment, 371-372  
 total yield of nitrogen, 380-381  
 yield of dry matter, 372-380
- Organic matter, effect of, on the moisture equivalent of soils, 165-167

- Oxygen, decomposition of cured and green clover in presence of a limited supply of, 145-146
- Phosphate Rock, the Effect of Leaching on the Availability of, to Corn (paper), F. C. Bauer, 235-251  
 experimental, 236-245  
 general discussion, 245-246  
 introduction, 235-236
- Phosphorus content of corn plant as affected by leaching when rock phosphate was used, acid phosphate,  $\text{NH}_4\text{NO}_3$  or  $\text{NaNO}_3$ , 240
- Plant composition, effect of leaching on, 240-241
- Plant Juices, Studies on the Reaction of (paper), A. R. C. Haas, 341-369  
 acid reserve of the juice of plants growing in the same environment, 359-360  
 agricultural plants with high actual and total acidities, 356  
 effect of—  
   chlorophyll upon the reaction of plant juice, 363-364  
   light and age on the reaction of the juice obtained from plants, 364-366  
   liming on the actual and total acidities, 346-356  
   standing on the actual and total acidities, 344-346  
 introduction, 341-342  
 is there a gradient of reaction in plants? 357-358  
 method of determining the acidity of plant juices, 342-344  
 the actual reaction of the juice from the succeeding year's growth of the same crop, 358-359  
 the alkali reserve of plant juice, 360-362  
 variation of reaction in different parts of plants, 356-357
- Plants, the Wilting of, as Related to the Water Supplying Power of the Soil (paper), Burton E. Livingston and Riichiro Koketsu, 469-485  
 abstract, 469-470  
 experimentation and results, 475-483  
 general discussion, 483-485  
 introduction, 470-472  
   porous-porcelain soil-points for the quantitative determination of the water-supplying power of the soil, 472-475
- Potato Scab, The Relation of Sulfur to Soil Acidity and to the Control of (paper), William H. Martin, 393-408
- Potential Biochemical Activity of the Spores of Soil Bacteria (paper), J. R. Neller, 329-340
- Prince, A. L., Blair, A. W., and (paper), The Lime Requirement of Soils According to the Veitch Method, Compared with the Hydrogen-Ion Concentration of the Soil Extract, 253-259
- Protozoa—  
 direct examination of soil for, 3  
 distribution of, in different soils, 11-13  
 enumeration of species of, in New Jersey soils, 6-9  
 relation of, to soil type, soil bacteria and molds, 13-14
- Protozoan Fauna of the Soils of New Jersey (paper), C. R. Fellers and F. E. Allison, 1-26  
 distribution in different soils, 11-13  
 enumeration of species of protozoa and algae in New Jersey soils, 6-9  
 methods, 2-3  
 present status of our knowledge concerning the character of the soil fauna, 3-6  
 relation of protozoa to soil type, soil bacteria and molds, 13-14
- Reaction of the Soil as Influenced by Green Manures (paper), L. P. Howard, 27-40  
 discussion of results, 37-38  
 experimental work, 29-37  
 factors influencing, 28-29
- Reduction Potentials of Bacterial Cultures and of Water-Logged Soils (paper), Louis J. Gillespie  
 oxidation and reduction study, 199-201  
 reduction potentials of microbial cultures, 204-209  
 reduction potentials of water-logged soils, 209-211  
 sourness of soils vs. acidity of soils, 211-212  
 technical discussion, 201-204  
 the significance of reducing conditions in soils, 212-214
- Robinson, R. H. (paper), Concerning the Effect of Heat on the Reaction between Lime-Water and Acid Soils, 151-157

- Rudolfs, W. (paper), Experiments on the Value of Common Rock Salt and Sulfur for Killing Live Stumps, 181-189
- Salt, Experiments on the Value of Common Rock, and Sulfur for Killing Live Stumps (paper), W. Rudolfs, 181-189
- Salts and Lime, Effect of Various Soluble, on Evaporation, Capillary Rise and Distribution of Water in Some Agricultural Soils (paper), M. I. Wolkoff, 409-436
- effect of—  
 chemical substances on the capillary rise of water in soils, 422-427  
 different chemical substances on evaporation of water from different soils, 411-416  
 different chemical substances on the moisture content of brown silt loam, 427-430  
 texture of soil on the rate of evaporation of water, 431-433  
 introduction, 409-410  
 practical deductions, 433-434
- Sand, the Influence of, upon the Concentration and Reaction of a Nutrient Solution for Plants (paper), John W. Shive, 169-179
- literature review, 169-170  
 methods of investigation, 170-171  
 results with unwashed sand, 175-178  
 results with washed sand, 172-175
- Schoonover, Warren R., Whiting, Albert L., and (paper), The Comparative Rate of Decomposition of Green and Cured Clover Tops in Soil; see Clover, Green and Cured, etc., 137-149
- Shive, John W. (paper), The Influence of Sand upon the Concentration and Reaction of a Nutrient Solution for Plants; see Sand, the Influence of, upon the Concentration, etc., 169-179
- Singh, Thakur Mahadeo (paper), The Effect of Gypsum on Bacterial Activities in Soils; see Bacterial Activities, etc., 437-468
- Sodium Carbonate and Sodium Chloride, Relative Absorption of, by Soil (paper), Thomas H. Kearney, 267-273
- Sodium chloride—  
 absorption by different soils, 267-268  
 adsorptive action of filters on, 45
- Sodium nitrate, effect of, on availability of rock phosphate, 237, 241-245
- Soil—  
 A New Soil Elutriator (paper), Willard Gardner, 191-197  
 acidity of, versus sourness of, 211-212  
 buffer action in, 202  
 clear extracts of, by the use of colloidal iron, 132-134  
 Comparative Rate of Decomposition of Green and Cured Clover Tops in (paper), Albert L. Whiting and Warren R. Schoonover; see Clover, Green and cured, etc., 137-149  
 Effect of Aeration and Other Factors on the Lime Requirement of a Muck Soil (paper), Seth S. Walker, 77-81  
 effect of concentration of soil solution on the freezing-point lowerings of roots and tops of plants, 219-224  
 effect of moisture content of, on the concentration of the cell sap in roots and tops of plants, 224-227  
 hydrogen-ion concentration in, 35-37, 115-136  
 Hydrogen-Ion Concentration Measurements of, in Connection with Their "Lime Requirements" (paper), Jacob S. Joffe, 261-266  
 moisture conditions of, from a dynamic point of view, 469-485  
 Moisture Equivalent in Relation to the Mechanical Analysis of (paper), Howard E. Middleton, 159-167  
 oxidation process in, literature review, 199  
 reduction potentials of water-logged, 209-211  
 relation of protozoa to type of, 13-15  
 Sampling Plots (paper), Firman E. Bear and George M. McClure, 65-75  
 Solution, its action on an indifferent electrode, 201  
 Spore formers in soils, methods of determination, 329-333  
 Stokes' law as applied to relative velocity of falling particles, 192-193
- Sulfur—  
 Experiments on the Value of Common Rock Salt and, for Killing Live Stumps (paper), W. Rudolfs, 181-189  
 used of, in potato-scab control, 393-408

- Temperature, effects of, on hydrogen-ion concentration of soils, 37-38
- Thorne, Charles E. (paper), Carriers of Nitrogen in Fertilizers, 487-494
- Truog, theory of, in regard to the feeding power of plants for insoluble phosphates, 235
- Veitch method—  
and hydrogen-ion concentration measurements in determining lime requirements, 256-258  
criticism of, 261  
factors affecting lime requirement as judged by the, 155-156
- Walker, Seth S. (paper), The Effect of Aeration and Other Factors on the Lime Requirement of a Muck Soil, 77-81
- Whiting, Albert L., and Schoonover, Warren R. (paper), The Comparative Rate of Decomposition of Green and Cured Clover Tops in Soil; see Clover, Green and Cured, etc., 137-149
- Wilson, B. D., Lyon, T. L., Bizzel, J. A., and (paper), The Formation of Nitrates in a Soil Following the Growth of Red Clover and of Timothy; see Nitrates, Formation of, etc., 53-64
- Wolkoff, M. I. (paper), Effect of Various Soluble Salts and Lime on Evaporation, Capillary Rise, and Distribution of Water in Some Agricultural Soils; see Salts and Lime, etc., 409-436



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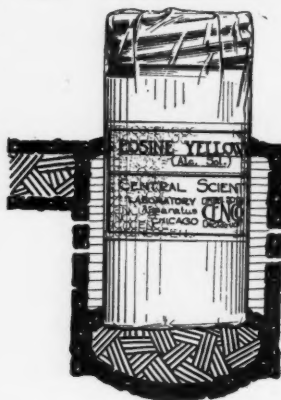
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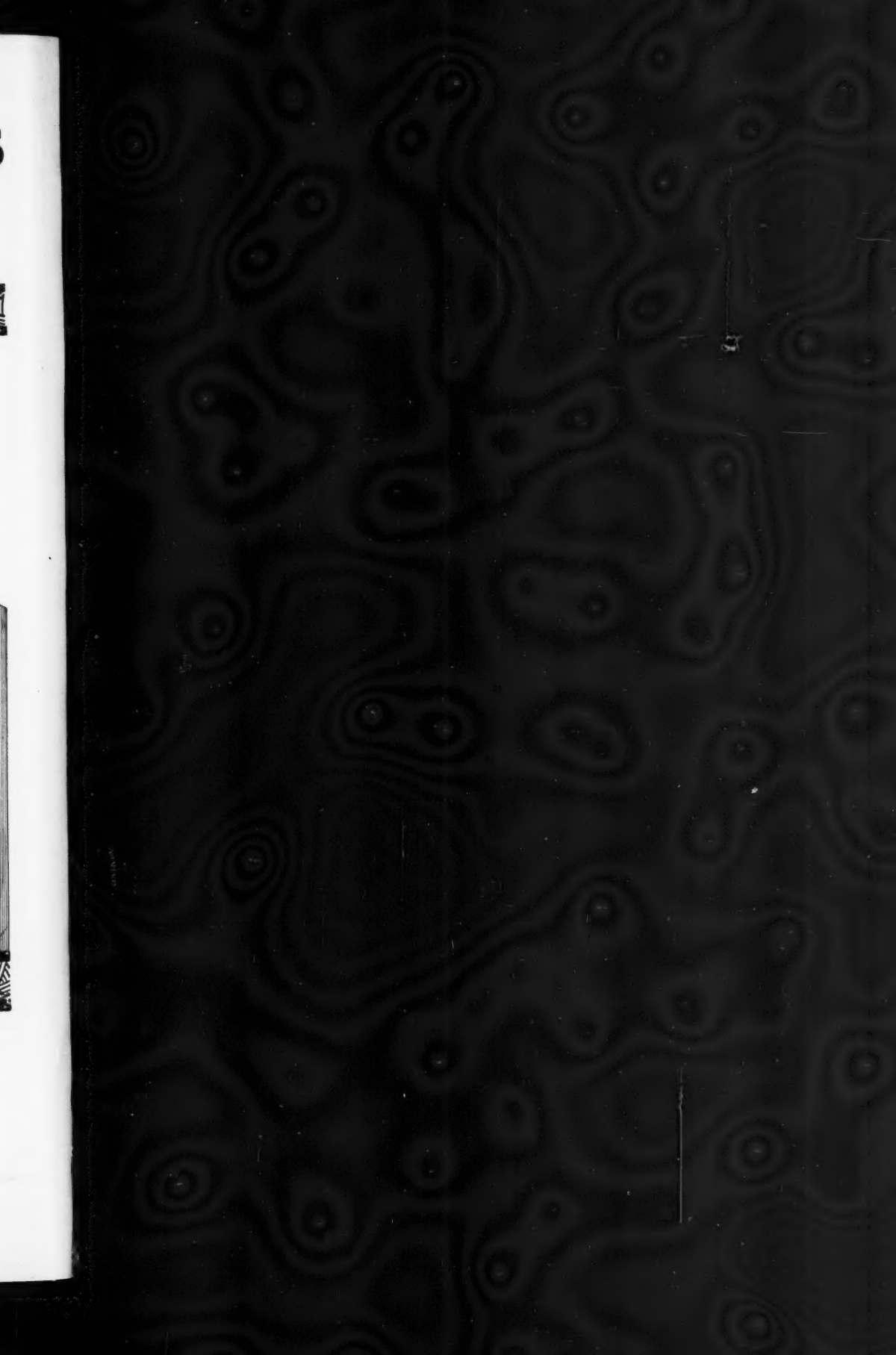
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